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Elements of Geology

# Elements of Geology

*With Reference to North America*

*By*

WILLIAM J. MILLER

*Emeritus Professor of Geology, University of California*
*at Los Angeles, California*
*Author of "An Introduction to Physical Geology,"*
*"An Introduction to Historical Geology,"*
*and many research papers*

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## PREFACE TO SECOND EDITION

THE second edition of this book represents a thorough revision both as to text matter and illustrations. It appears in a larger and more attractive format and it is the author's hope that it will prove more valuable and teachable than was the first edition.

Valuable suggestions were made to the author by users of the first edition and these have been employed in the preparation of this revised edition. The book is somewhat enlarged, mainly by reason of a larger number of illustrations. Various block diagrams and photographs have been added and a number of small pictures have been enlarged so as better to display detail. New and more modern pictures have been substituted for many of the illustrations in the first edition and all paleogeographic maps and nearly all maps showing areas of outcrops of rock systems have been redrawn. A particular effort has been made to coordinate the pictures and text. All diagrams and pictures not credited to others are by the author.

The revised text includes many of the newer findings in the science of geology and a number of topics that were omitted from the previous edition. The chapter on "Instability of the Earth's Crust" now appears as Chapter II, not only because this subject can be well presented early in the course but also because it lends itself unusually well to arousing and stimulating the student's interest in geology early in his study.

The material on the descriptions of common minerals has been reduced. Many changes have been made in Chapter X on "The Sea and Its Work" which has been almost entirely rewritten. Important changes appear in the chapters on "The Archeozoic Era," "The Proterozoic Era" and "The Cenozoic Era." In the latter section the rocks and physical history of the era are first considered, thus avoiding a largely arbitrary break in the discussion of the Tertiary and Quaternary changes which have led up to present-day conditions. The Ice Age is then conveniently treated in a separate chapter. Finally, the life of the Cenozoic is considered as a whole thus again avoiding an unnatural break, and giving a more unified picture of the life of the era. The important

Pacific Coast Tertiary and the geologic history of man are both dealt with more fully and in the light of the most recent knowledge.

The author desires to express his gratitude to those who have been helpful with suggestions.

WILLIAM J. MILLER

University of California at
Los Angeles, California
October, 1938

## PREFACE TO FIRST EDITION

THIS book is an abridged form of the author's "Introduction to Physical Geology" and "Introduction to Historical Geology." It is intended to serve as a text for a one-semester course in general geology.

It has been so written that a formal knowledge of neither chemistry, physics, nor biology is a prerequisite for a reasonable understanding of its contents. The instructor can ordinarily supply the most needed information along these lines in the class room and laboratory lectures and discussions.

Field trips should be made to illustrate as many of the principles of the science as time and conditions will permit. Such outdoor work greatly aids in making the study more realistic and interesting. Laboratory work should be, as far as possible, directly correlated with the class room and textbook work. The student should study specimens of minerals and rocks, and also models, maps, and diagrams.

Concrete examples are freely used to illustrate important facts and principles, and, since geology is essentially an historical science, the historical order has been emphasized in the treatment of the special topics and concrete examples.

Careful attention has been given to the arrangement of the subject-matter. The very nature of the subject is such, however, that some repetition and anticipation are unavoidable no matter what the arrangement. The purpose has been not only to make the order of treatment logical, but also to avoid repetition and anticipation as far as possible.

In the second part of this book more introductory space is devoted to a discussion of broad fundamental principles of historical geology than is customary in textbooks. The rocks and physical history are also more distinctly emphasized than the paleontology, and it is hoped that this feature will appeal to teachers who are not specialists in paleontology as well as to students who have little or no technical knowledge of biology.

Much time and thought have been devoted to the gathering of the illustrations which form an essential part of the book. All of the views and diagrams illustrate important facts and principles of the science, and, therefore, they should be carefully studied in connection with the text.

Among the numerous original sources of photographs, special mention should be made of the United States Geological Survey, the United States National Museum, the United States Reclamation Service, the United States Forest Service, the National Park Service, the New York State Museum, and the American Museum of Natural History. The Macmillan Company, Henry Holt and Company, Ginn and Company, D. Appleton and Company and John Wiley and Sons have generously allowed the use of various cuts.

Due acknowledgment is here made for the help obtained not only from various teachers of geology, but also from the various manuals, textbooks, and special treatises on geology, and from many publications of the United States Geological Survey.

Corrections and suggestions for the improvement of the book will be heartily welcomed.

WILLIAM J. MILLER

University of California at
Los Angeles, California
January, 1931

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# ELEMENTS OF GEOLOGY

## WITH REFERENCE TO NORTH AMERICA

# PART I. PHYSICAL GEOLOGY

## CHAPTER I

## INTRODUCTION

### Definition of Geology

Geology (meaning literally "earth science") deals with the history of the earth and its inhabitants as recorded in the rocks. Broadly considered, the science may be divided into physical geology and historical geology. *Physical geology* deals with the materials of the earth; earth-crust movements; the structure of the earth; and the processes and agencies by which the earth has been for many millions of years, and is being, modified, including such agencies as weather, wind, streams, glaciers, sea, organisms, volcanoes, subterranean waters, and lakes. *Historical geology* deals with the records of the successive events of earth history, and with the history and evolutionary changes of the organisms which have lived upon the earth. *Geography* deals with the distribution of the earth's physical features, in their relation to each other, and to the life of sea and land, especially human life and activity. Geography may, therefore, be regarded as the outward and present-day expression of geological effects. Geology includes geography as cause includes effect. *Physiography* deals with the relief features of the earth and the geologic laws which govern their origin.

### The Scope and Significance of Geology

The person of ordinary intelligence is, unless he has devoted some study to the matter, very likely to regard the great variety of physical features and life of the earth as practically unchangeable, and to think that they were essentially the same in the beginning of the earth's his-

tory as they are now. But the study of geology has firmly established the great fact that the face of the earth, and the life upon it, represent merely a single phase of a tremendously long history which has involved many profound and far-reaching changes.

The following concise statements of some of the more definite and important conclusions regarding earth changes may serve to give a fair conception of the general scope and significance of geology. For untold millions of years rocks at and near the surface of the earth have been crumbling under the weather; streams have been sawing incessantly into the lands; the sea has been eating into continental masses; the winds have been sculpturing desert lands; and, more locally and intermittently, glaciers have plowed through mountain valleys, and even vast sheets of ice have spread over considerable portions of continents. The outer shell (so-called "crust") of the earth has shown marked instability throughout geologic time. Slow upward and downward movements of the lands relative to sea level have been very common, in many cases amounting to thousands of feet. Various parts of the earth have been, and are being, affected by sudden movements (resulting in earthquakes) along fractures in the outer crust. During the eons of geological time, vast quantities of molten materials have, at intervals, been forced not only into the earth's crust, but also often out upon the surface. Mountain ranges have been brought forth and cut down, and sometimes rejuvenated. Sea waters have spread over many parts of what are now continental areas. There have been repeated advances and retreats of the sea over many districts. Lakes have come and gone. Plants and animals have inhabited the earth for many millions of years. In earlier known geological time the organisms were comparatively simple and low in the scale of organization. Through the succeeding ages higher and more complex types were gradually evolved until the highly organized forms of the present time, including human beings, were produced.

## Geological Time

The great importance of the time element in the study of geology cannot be too strongly impressed upon the reader. The length of time of known human history is, indeed, very short as compared to that of known geological time. The one is to be measured by thousands of years, and the other by tens, or possibly hundreds, of millions of years. To the geologist a lapse of hundreds of thousands of years is a "short" time. "The flowing landscapes of geologic time may be likened to a

kinetoscopic panorama. The scenes transform from age to age; seas and plains and mountains of different types follow and replace each other through time, as the traveler sees them succeed each other in space. At times the drama hastens, and unusual rapidity of geologic action has, in fact, marked those epochs since man has been a spectator upon the earth. (Geological) science demonstrates that mountains are transitory forms, but the eye of man through all his lifetime sees no (important) change, and his reason is appalled at the conception of a duration so vast that the millenniums of human history have not accomplished the shifting of even one of the fleeting views which blend into the moving picture" (J. Barrell).

The known history of the earth has been more or less definitely divided into great eras, and these in turn into periods and epochs. In the accompanying table, the era and period names, except those representing the earlier times, are mostly world-wide in their usage. Epoch names are too numerous, and usually too local in application, to be included in the table for our general use in this book.

TABLE OF MAIN GEOLOGICAL DIVISIONS

| *Era and group* | *Period and system* |
|---|---|
| CENOZOIC | Quaternary<br>Tertiary |
| MESOZOIC | Cretaceous<br>Jurassic<br>Triassic |
| PALEOZOIC | Permian<br>Pennsylvanian (Upper Carboniferous)<br>Mississippian (Lower Carboniferous)<br>Devonian<br>Silurian<br>Ordovician<br>Cambrian |
| PROTEROZOIC | Keweenawan<br>Huronian |
| ARCHEOZOIC | Timiskaming<br>Keewatin |

## BRANCHES OF GEOLOGICAL SCIENCE

*Mineralogy* is the study of minerals which are natural, homogeneous substances of definite (chemical) composition. With the exception of a relatively very slight amount of organic material, minerals constitute the whole lithosphere as far as it is known.

*Petrology* is the study of rocks, which are more or less extensive constituents (or formations) of the earth's crust, and which are nearly always made up of mixtures of minerals, or more rarely, of masses of single minerals.

*Dynamical geology* is the study of the agencies and processes whereby


FIG. 1. Map of North America, showing its main political and physical divisions.

the outer portion of the earth has been, and is being, modified. Important dynamical agents are weather, wind, running water, the sea, glaciers, igneous actions, and earth-crust movements.

*Physiography*, sometimes called *physical geography*, deals with the topography of the earth's surface and the manner of its origin. It is

closely related to dynamical geology because it involves a consideration of the same modifying forces.

*Structural geology* is the study of the arrangement or architecture of the materials of the earth. In a real sense it includes a study of the materials themselves, especially the rocks, and so it may be regarded as including petrology, and possibly mineralogy.

*Paleontology* deals with the plant and animal life of the geological ages as shown by the fossil remains of organisms found in the rocks.

*Stratigraphy* deals with the arrangement and succession of the strata of the earth.

*Paleogeography* is the study of the geographic conditions of the earth during former (geologic) ages, especially with the relations of lands and seas. Paleontology, stratigraphy, and paleogeography are really subdivisions of *historical geology*, which, as already defined, deals with the successive events of earth history, including the history of organisms.

*Economic geology* is the practical application of geology to the arts and industries. It deals with geological products of value to mankind, such as coal, petroleum, ores of the metals, building stones, salt, gypsum, etc.

# CHAPTER II

## INSTABILITY OF THE EARTH'S CRUST

### DIASTROPHISM

**Meaning of Diastrophism.** The outer shell of the earth is unstable. Overwhelming evidence establishes the fact that it has been so for many millions of years. To the geologist the old notion of a *terra firma* is outworn. The inhabitants of an earthquake country could never have originated the idea of an unshakable, immovable earth. Earth-crust movements may vary from those which are so slow as to be imperceptible to those which are quick and violent. They may be upward, or downward, or sidewise. They may affect only small, local areas, or they may involve a large portion of either a continent or an ocean basin. The general term *diastrophism* covers all actual movements of the earth's crust of whatever kind or degree.

It is very important that the student should, early in his study of geology, be convinced of the fact that crustal disturbances (often profound ones) actually do take place, because this is one of the most fundamental tenets of the science. Sudden movements are, in the popular mind, more impressive and significant than the slow movements because they are more localized and evident, and frequently accompanied by destruction of life and property, as well as by obvious, though minor, changes in topography. Crustal movements which take place slowly and quietly are, however, often of much greater significance in bringing about profound physical geography changes, such as those which have affected the earth during its eons of recorded history.

There are, in a general way, two types of diastrophism. In one type, known as *epeirogenic movement*, there is either elevation or subsidence of a large or small portion of the earth's crust without notable compression or crumpling (folding) of the rocks, which latter may not have their former attitude changed, or they may become gently warped (upward or downward), or more or less tilted. Fracturing and dislocation (faulting) of the rock masses often accompany such an epeirogenic movement which not uncommonly affects a considerable portion of a continent or sea floor. In the other type, known as *orogenic movement*,

a relatively long, narrow belt or zone of the earth's crust is subjected to a force of compression, causing the rocks (usually strata) to be more or less crumpled (folded) and upraised into a mountain range. Our present purpose is merely to call attention to the general nature of epeirogenic and orogenic crustal disturbances, both of which are of great geological importance. Their significance will be better understood after a study of succeeding pages of this book, particularly in Chapters VI and XIII.

Various geological agencies, such as weathering, winds, streams, glaciers, and the sea, operate externally upon the earth, their general tendency being to cut down (erode) the lands and carry their waste into the sea. Such agencies would, if not interfered with, completely level the lands and destroy the continents in the course of time. Geological research has made it certain that such external agencies have operated upon the earth for countless ages, and yet the continents have by no means been destroyed. This is because the external agencies are now, and have been throughout recorded earth history, opposed by forces operating from within the earth, that is, by diastrophic forces. Through diastrophism, elevation and re-creation of lands have at least kept general pace with the external forces of destruction; ocean basins have sunk relative to continental areas, causing frequent withdrawals of sea water from areas temporarily submerged; and tremendous volumes of molten materials have been forced not only into the earth's crust, but also out upon its surface. Through lowering of land areas diastrophism has, in many cases, helped to destroy them as such, but on the average, diastrophic forces which upbuild lands (relative to sea level) have predominated over forces which have lowered them.

**Datum Surface.** In land surveying the *datum* is the point, or horizontal line, or surface from which heights or altitudes of points or places are measured or reckoned. The geologist, for his study of the amount and rate of upward and downward movements of the earth's crust, must have some point, line, or surface as a datum. The sea surface is in general the most satisfactory datum, for it maintains an average tidal level (within narrow limits) throughout its vast extent. At the bottom of each topographic map published by the United States Geological Survey there is a statement that "datum is the mean sea level" which means that all elevations recorded on the map are reckoned from the average tidal level of the sea. It should not, however, be assumed that the sea level is, and always has been, fixed and constant. Not only is it a somewhat warped or irregular surface at any given

time, but also it may rise or fall very appreciably. The records of earth history reveal the fact that many changes of level between land and sea have taken place. Among the minor changes it is often impossible to tell whether it was sea level or land, or both at the same time, which rose or fell. In such cases, therefore, terms like uplift and subsidence, or elevation and depression, as applied to lands are commonly used by geologists in a relative sense only.

**Evidences of Elevation of Land.** Only a very few of the thousands of definitely known cases of change of level between land and sea

FIG. 2. Part of the shore of Disenchantment Bay, Alaska, which was suddenly uplifted 47 feet at the time of the great earthquake in 1899. (After Tarr and Martin, U. S. Geological Survey.)

will here be briefly described. The examples are chosen to illustrate the more common principles involved. Some of these movements have taken place within the last few thousand years of clearly recorded human history, while others are much older, being records of the geological past.

There are many authentic instances of moderate uplift of the land which have come under the observation of man. A sudden diastrophic movement, resulting in a terrific earthquake, caused uplift of a part of the coast of Alaska near Yakutat Bay to a maximum of 47 feet in 1899 (Fig. 2).

Direct measurements by observing marks along the Baltic shore have

proved that most of Sweden (excepting its southern portion) has risen to a maximum of seven feet in the north during the last 175 years.

Old docks on the island of Crete in the Mediterranean Sea have risen as much as 27 feet within the last 2000 years.

Several rock ledges which were at, or a little below, sea level hundreds of years ago in the Baltic Sea are now distinct islands well above the sea surface.

About 100 years ago a portion of the coast of Chile rose abruptly several feet, causing a severe earthquake.

FIG. 3. Part of a great recently uplifted marine terrace facing the sea at an altitude of about 125 feet. The road is on the terrace. Two higher terraces show in profile in the distance. San Pedro Hills, near Los Angeles, California.

Evidence from old elevated shore features, including so-called "raised beaches," is very important. Thus, a succession of terraces cut by the waves of the Pacific Ocean are plainly preserved on the western face of the San Pedro Hills near Los Angeles, California. The highest and oldest of these terraces is over 1000 feet above the sea, while the lowest, containing many sea shells, is about 100 feet above tide. A somewhat similar succession of terraces occurs on San Clemente Island, about 50 to 60 miles off the southern California coast (Fig. 3). Wave-cut terraces with remnants of rock not removed by the waves, occur well above sea level as illustrated by Figure 4. Sea caves formed by wave action are also above sea level in many places. In Scotland such caves lie fully 100 feet above tide water. Raised beaches and shore forms in well-preserved condition up to hundreds of feet above sea level are common in many other parts of the world, as for example Scandi-

navia, Labrador, west coast of South America, and the West Indies. Many of these raised beaches are notably warped or tilted, thus proving that actual earth-crust movements have taken place, and not merely a lowering of sea level. A good illustration of this principle is found in the valley of Lake Champlain where marine deposits, formed since the Ice Age, now lie hundreds of feet above the present lake level, their altitude increasing northward at the rate of more than two feet per mile.

Remains (fossils) of marine organisms at various altitudes up to many thousands of feet afford very strong evidence of uplift of land

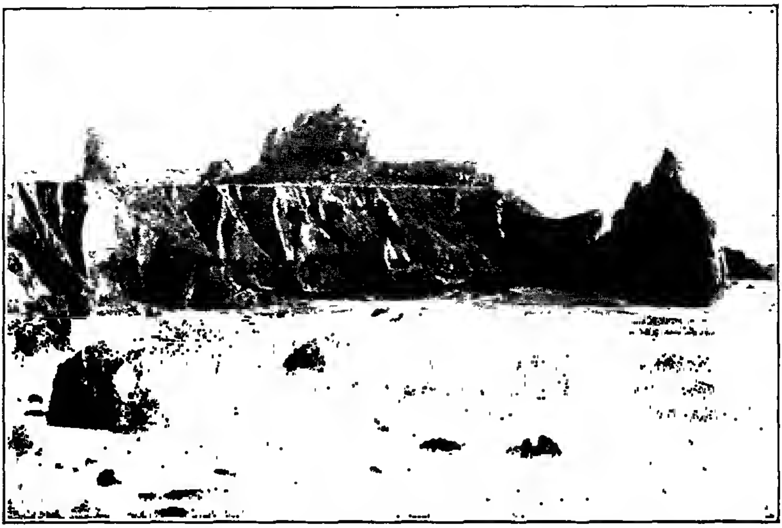


FIG. 4. Elevated marine terrace with remnants of rock which were not cut away by the ocean waves. Near Port San Luis, California. (After G. W. Stose, U. S. Geological Survey.)

relative to sea level. There are almost countless numbers of examples. Thus, in the Rocky Mountains of the western United States and Canada, sea shells occur in many places at altitudes of from one to over two miles. The same is true in many other mountain ranges. In Tibet and northern India (Himalayas) fossil marine organisms have been found at altitudes of from three to four miles. In many of these cases the marine fossils are in highly disturbed (folded) strata of geologically recent age. Furthermore, strata of the same geological age lie at all sorts of altitudes in different parts of the world. For these reasons, and in the light of what we have already learned regarding the sea level as a datum, it is evident that such great, often differential, changes of level must be diastrophic rather than simply effects of lowering of the sea surface.

Well in the interior of continents, differential earth-crust movements are also known to have taken place. Thus high-level beaches of the vast ancestor of Great Salt Lake have been warped notably. Certain beach lines of ancestors of the Great Lakes have been tilted out of their original horizontal positions to the extent of hundreds of feet, since the Ice Age.

**Evidences of Subsidence.** In certain parts of Crete old docks have (as already stated) been raised as much as 27 feet above water, while

FIG. 5. An aerial view of the gorge of the Hudson River in southeastern New York. Because of geologically recent sinking of the region, tide water occupies the valley. (Fairchild Aerial Surveys.)

in other portions of the same island remains of similar structures are below sea level, thus proving differential crustal movement.

Portions of the coast of Greenland have sunk recently, as proved by the fact that certain human structures are there below tide water.

Submerged forests prove recent sinking of land in many parts of the world, excellent examples being around the coast of England especially in Cheshire and Lancashire, and on the shores of the English and Bristol Channels, where numerous stumps of trees are well below tide-water level.

A good example of rapid movement of portions of a region in opposite directions at the same time is the Yakutat Bay region of southern Alaska in 1899 where part of the coast suddenly rose as much as 47 feet, while another portion sank below tide level (Fig. 2).

Submerged valleys afford very strong evidence of subsidence, often to the extent of many hundreds of feet. A fine example of such a "drowned river valley" is the Hudson Valley of New York. Regional subsidence to the extent of hundreds of feet has allowed tide water to enter this river-cut valley for 150 miles (Fig. 5). Since the Ice Age there has been a partial re-elevation of this subsided region. The Hudson Valley is also very clearly traceable by soundings across the floor of the sea for 100 miles east of New York City (Fig. 6), proving that the earth's crust has there subsided fully 1000 feet since the valley was carved out (eroded) by the river. Notable sinking of the land also has caused a flooding of the lower St. Lawrence Valley by tide water. San Francisco Bay was formed by geologically recent sinking of a portion of the Coast Range region, the Golden Gate marking the submerged channel of the combined Sacramento and San Joaquin Rivers.

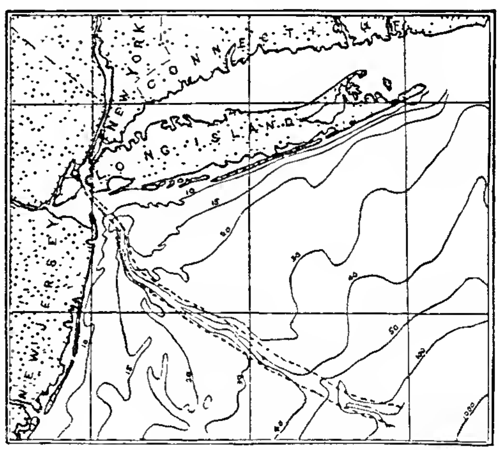


Fig. 6. Map showing the submerged channel of the Hudson River. Figures show depth of water in fathoms. (By the author, data from Coast and Geodetic Surveys.)

In the study of examples of earth-crust movements, it should be clearly understood that a single district may show plain records of both depression and elevation. In such a case upward or downward movement may be succeeded by movement in the opposite direction. This principle is finely illustrated by the coast of Maine where the whole region sank hundreds of feet in recent geological time, allowing tide water to flood the mouths and lower valleys of all the rivers, thus giving rise to the deeply indented shore line. A partial re-elevation (of 100 to nearly 200 feet) has taken place as proved by the clay deposits with marine shells along the coast, and for miles up the valleys.

**Cause of Diastrophism.** The fact of diastrophism is thoroughly established. There is rather general agreement among geologists as to the proximate cause of diastrophism, but not in regard to the ultimate cause. The proximate cause appears to be unequal contraction, or shrinkage, of the earth. There is much evidence that the earth, or at least its outer (shell) portion, is heterogeneous, and that it has been shrinking for many millions of years. The fact that strata which, at various times and places, accumulated under water layer upon layer, in horizontal position, to thicknesses of many thousands of feet, have been highly crumpled and folded into mountain ranges (Figs. 199, 200) proves earth-crust shortening. In the development of a typical mountain range by this process, the crustal shortening is commonly 5 to 20 miles or more.

A general conception is that, as the earth shrinks, its outer shell or crustal portion is subjected to stresses and strains which are relieved occasionally by crumpling of zones of relatively weak rocks, usually strata. In other cases land areas may move upward or downward without crumpling, and with or without tilting. If the earth is a shrinking body, its whole surface must be undergoing a general downward movement toward the center. But, since the earth is a heterogeneous body, not all portions move downward at the same rate, and so the portions which move down less rapidly tend to stand out in relief, giving the appearance of uplift, although their actual movement is also downward.

Viewed very broadly, the earth may be divided into four segments —two oceanic (Atlantic and Pacific), and two continental (Eurasia-Africa and the Americas). It has been proved by actual test (gravity determination) that the materials of the oceanic segments are heavier than those of the continental segments. The oceanic segments are probably moving toward the earth's center faster than the continental segments. At the same time the great earth-segments are being more or less divided or broken up into smaller masses, some of which may be subjected to pressure in such manner as to cause localized actual uplifts, as in the folding and uplift of many mountain ranges.

It should be made clear, however, that the ultimate cause of diastrophism is, in our present state of knowledge, far from definitely known. That is, we do not surely know why the earth contracts, why it shrinks so unequally, or just how the shrinkage produces the various phenomena of diastrophism.

## Earthquakes

**Causes of Earthquakes.** Any sudden movement of a portion of the earth's crust, due to a natural cause, which produces a shaking or trembling of the ground is called an *earthquake*. The study of earthquakes is known as seismology. The impulse or shock which gives rise to the trembling originates at a greater or less depth below the earth's surface. Such shocks are known to originate in various ways.

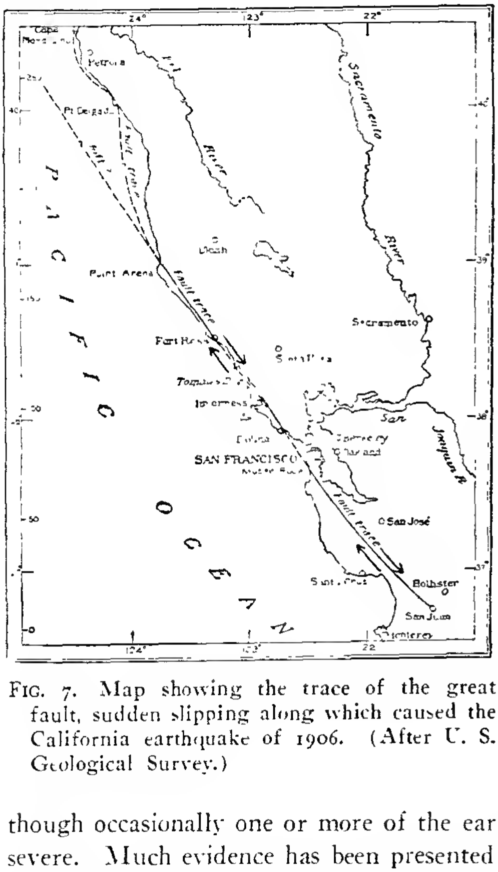



Fig. 7. Map showing the trace of the great fault, sudden slipping along which caused the California earthquake of 1906. (After U. S. Geological Survey.)

Studies during the last fifty years have made it plain that the principal cause of earthquake shocks is the sudden slipping of portions of the earth's crust past each other along fractures, known as faults. The sudden shifting furnishes the impulse which sends out the vibrations or waves into the surrounding portions of the earth. The first great movement is usually followed for days, or even months, by a succession of after-shocks which generally decrease in number and intensity, though occasionally one or more of the earlier after-shocks may be very severe. Much evidence has been presented recently to support the view that the fracturing (faulting), of the rocks is the result of elastic strains which accumulate by slow shifting of neighboring portions of the earth's crust in opposite directions until the rocks can no longer withstand the strains, and that the only appreciable, sudden mass movements, at the time of the earthquake, takes place on one or both sides of the fracture, and within relatively few miles of it. Such an earthquake may be regarded as simply a sudden manifestation of slower diastrophic move-

ment. In an earthquake of the kind just explained, the main zone of shock, and, therefore, of destruction, is linear because the vibrations originate in the line of fracture. A very severe earthquake may be caused by a sudden slipping of ten to forty feet along a line of fracture fifty to several hundred miles long.

Another, though much less important, cause of earthquakes is volcanic activity. A violent or explosive eruption often causes the earth in its vicinity to quake. Earthquakes not uncommonly precede volcanic eruptions. In still other cases shocks often occur unaccompanied by eruptions in volcanic regions. It is generally believed that such earthquakes are caused by sudden, subterranean yielding of the earth's crust under the influence either of increasing pressure of volcanic gases or of shifting positions of molten rocks imprisoned within the earth and struggling to escape. Earthquakes of volcanic origin are, as a rule, much less severe and more limited in extent than those caused by fracturing of the earth's crust. In volcanic earthquakes the impulse or shock is centralized, rather than linear as in the fracture type of earthquake, and so the vibrations radiate from the center of disturbance into the surrounding region.

"Very often earthquakes and volcanoes are associated both in space and time. But the ordinary earthquake is not the effect of volcanic action. Both quake and volcano are effects of a common cause, the sudden fracture of a strained crust. In 1914 southern Japan was shaken, nearly simultaneously, at two points. From them seismic waves spread out. These shocks were caused by breaking of the crust. The fracturing changed the pressure conditions of the lava underlying the volcanic cone of Sakurajima. The cone, therefore, erupted violently. Here, then, we have the special case of eruption and shocks, both developed through displacement of the solid crust. Both were due to a common cause." (Daly.)

A minor cause of earthquakes is the force of impact of a great landslide or avalanche when it strikes relatively flat land at the base of a mountain. Submarine slides also are believed to be a cause of earthquakes, as for example in some parts of the western coast of South America.

Another cause of small shocks is the sudden caving in or collapse of the roof of an underground opening (cavern).

The falling of a large block of rock from a cliff or the crest of a waterfall often gives rise to a slight shock. This has happened at Niagara Falls.

**Frequency, Duration, and Extent of Shocks.** Earthquakes are exceedingly common. It is probably true that the surface of the earth is at no given time entirely free from earthquake vibrations. Earthquake recording stations in many parts of the world bear out this statement. Fully 30,000 earthquakes recognizable by the senses occur each year. A great many of these shocks are of course very slight. Only occasionally are the shocks very severe. Earthquakes which cause considerable loss of life and property occur, on the average, perhaps not more than once or twice a year. Earthquakes of varying degrees of intensity have been recorded in Japan at the rate of several per day, and in California at the rate of several per month, for many years, but most of them have been of very low intensity.

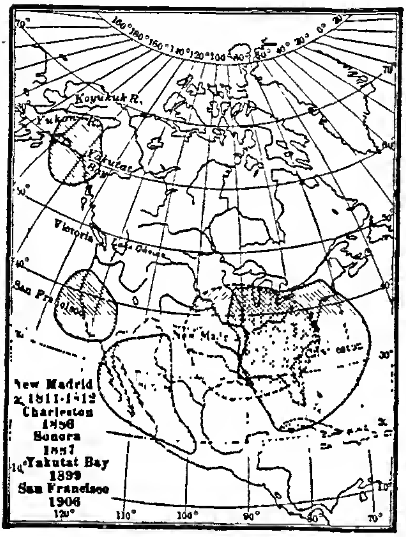



FIG. 8. Map of North America showing areas sensibly affected by some great earthquakes. (From Tarr and Martin's "Physiography," by permission of the Macmillan Company.)

In New England, which is a region generally regarded as exempt from earthquakes, hundreds of shocks have been recorded within the last 300 years. Probably all but one (eastern New England, 1755) of these have been slight shocks which have caused little or no destruction. Distinct shocks occurred in 1925 and 1929.

The vibrations of earthquake shocks which are sensible to human beings last from a few seconds to several minutes. In general, the greater the intensity of the shock, the longer it lasts. The average duration of shocks of considerable intensity is perhaps from one to two minutes.

Earthquakes shocks of sufficient intensity to be noticed by man vary greatly in regard to the size of the region throughout which they may be felt. They may be felt over areas no larger than villages, or over considerable portions of continents. The violent California earthquake of 1906 was felt over an area of several hundred thousand square miles. The Charleston, South Carolina, earthquake of 1886 was actually felt by people over an area of 2,000,000 square miles, and in states as far

away as Wisconsin and those of southern New England (Fig. 8). Severe earthquakes, like those just mentioned, actually shake the whole earth, though not enough to be generally recognizable by the senses, as proved by delicate recording instruments in many parts of the world.

**Nature of Earthquake Waves and Vibrations.** In our consideration of earthquakes, the reader should clearly understand that the earth, instead of being an excessively rigid body, is, as a matter of fact, more or less elastic. A sudden impulse, therefore, sets a portion of the earth in vibratory (or earthquake) motion in somewhat the same manner that a large mass of jelly is set in vibration by a sharp tap on its containing vessel. The vibrations or tremblings travel out in wavelike form into the earth in all directions from the source of the shock. Earthquake waves travel ordinarily at the rate of about two to three miles per second.

When, as a result of a sudden shock, vibrations are set up in the earth, as in any solid, they take the form of waves within the earth which are of two important kinds, namely, *waves of compression* and *waves of distortion.* In the compressional (or longitudinal) waves, the particles move (vibrate) backward and forward in the direction along which they are transmitted. In the distortional (or transverse) waves, the particles move (vibrate) in a direction across the path of the wave transmission. On reaching the surface of the earth the transverse waves cause the rocking motion of the earthquake. Another kind of wave travels along the surface, and near surface, portion of the earth. The exact nature of this wave is not known, but in a great earthquake it throws the ground into a series of actual undulations, somewhat like waves of water, which may be observed to rise in long, low, very swiftly moving waves, causing trees or tall structures to sway violently. The main shock is by some believed to be due to the joint action of transverse and surface waves. At distant points on the earth the kinds of earthquake waves are more or less separately recorded by a delicate instrument called a seismograph, as mentioned under the next heading. The actual amount of movement of a particle of earth during the passage of an earthquake wave, even the surface wave, generally is to be measured only by inches or fractions of an inch. The amount of bodily slipping or shifting of the earth's crust along and near the line of an earthquake fracture (or fault) commonly ranges up to 20 feet or more.

**Seismographic Records.** Instruments of great precision and delicacy, called *seismographs,* have been constructed for the purpose of recording earthquake shocks. The fundamental principles involved are

simple, but in actual construction a good seismograph is a complicated machine, a description of which will not here be attempted. A seismographic record is called a *seismogram.*

**Effects of Shocks.** Earthquakes are generally classed among the most terrifying of all natural phenomena because of the awful loss of life and property which sometimes results from them. Earthquakes also cause certain changes in the earth's surface. In this connection it is important to keep in mind cause and effect of earthquakes. Thus the actual sudden shifting of portions of the earth's crust along either side of the line of fracture (fault), which is often accompanied either by the development of a fissure, or a steep declivity along the line of fracture (Fig. 72), is the cause rather than an effect of an earthquake. Numerous changes are, however, direct effects of shocks, even at considerable distances from the seats of disturbance. Thus, the vibrations often cause landslides, especially in mountainous regions. Cracks and fissures, and local small elevations and depressions of the land, often occur, and they may affect surface drainage. The disturbance of the earth's crust may cause old springs to stop flowing, or new springs to develop. An extraordinary subsidence occurred during the Indian earthquakes of 1819 when a tract of land covering some 2000 square miles near sea level actually sank a little below sea level. It very rarely happens, however, that even a great earthquake produces more than very minor topographic effects.

**Submarine Earthquakes and Tsunamis.** Many earthquakes are known to take place under the ocean, mostly within the belts below described, but obviously our knowledge concerning them is more meager than it is concerning earthquakes on land. Submarine disturbances are felt on shipboard, and ocean cables are sometimes broken by them. Among very recent severe submarine earthquakes, mention may be made of one which took place on the sea floor off the coast of Chile in the fall of 1922, sending a series of great sea waves upon the land. Another occurred somewhere under the south Pacific Ocean, sending water waves upon the shores of Hawaii. Such sea waves, known as *tsunamis*, are caused by the sudden movements of portions of the sea bottom. They are often miscalled "tidal waves."

Tsunamis may be from 100 to 200 miles from crest to crest, and 20 to 40 feet high, where they originate. They travel with a speed of hundreds of miles per hour, but in the open sea they are scarcely noticeable because they are so broad and relatively low. Tidal gauge records show that certain tsunamis from Japan have crossed the Pacific Ocean,

with height diminished to less than a foot, in about 12 hours. If a great tsunami starts reasonably near a coast it will pile up in passing into shallow water, and it may sweep upon the land in the form of a huge surge or breaker from 25 to 100 feet high. Such an earthquake sea-wave swept over part of the city of Lisbon, Portugal, in 1755 with destructive violence, and another in Chile (1868) carried a United States war vessel half a mile inland, and left it stranded.

**Distribution of Earthquakes.** Although earthquakes are very widely distributed, so that no part of the earth seems to be immune from at least slight tremors, nevertheless most of them by far occur within two great rather crudely defined belts or zones, as shown by Figures 9 and 10. One of these belts almost encircles the great Pacific Ocean, and the other extends in a nearly east-west direction around the earth through southern Asia, the Mediterranean district, the Azores, the West Indies, Central America, the Hawaiian Islands, and the East Indies. In a study of 170,000 earthquakes, Montessus de Ballore found that nearly 95 per cent of them occurred within these two belts. It is an illuminating fact not only that the great majority of active and recently active volcanoes, but also that most of the youngest mountains of the world are located within the two great earthquake belts. In fact it seems rather clear that both earthquakes and active volcanoes are only surface, or near-surface, manifestations of the great diastrophic forces which, at the present time, are operating chiefly within these two belts, but in the present state of our knowledge we cannot say why these great forces are there so active. A study of the ancient records of the earth (historical geology) shows that diastrophism has by no means always been especially vigorous within these two belts.

FIG. 9. Map of the eastern hemisphere showing the principal earthquake regions. (After M. de Ballore.)

FIG. 10. Map of the western hemisphere showing the principal earthquake regions. (After M. de Ballore.)

**Energy of Earthquakes.** The energy involved in the more severe earthquakes of fault-slip origin staggers the imagination. Reid has estimated that the energy of the San Francisco earthquake of 1906 was sufficient to raise a cubic mile of rock 6000 feet, or equal to 800,000,000 times the muzzle energy of a great cannon. But this energy was far less than that of many other well-known earthquakes. Thus, according to Sieberg, the

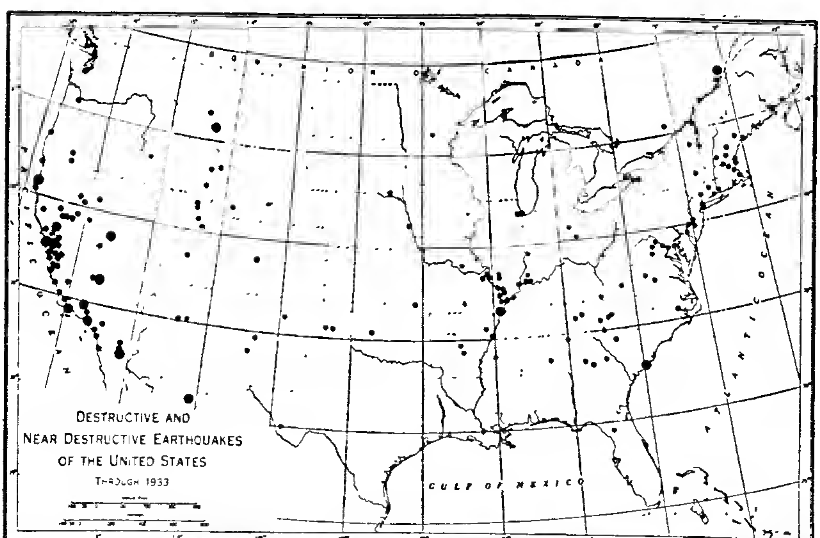



FIG. 11. Earthquakes occur in some regions much more frequently than in others, but it would be a mistake to suppose that they are confined to a few localities. The United States as a whole is comparatively free from earthquakes, yet, as the map shows, there is no section of the country that has not at some time experienced their effect. (From Bulletin of the Seismological Society of America.)

energy of the Japanese earthquake of 1891 was about eleven times as great as that of San Francisco, 1906. Others were still greater in energy.

Someone has estimated that the energy of the San Francisco earthquake was enough to run a battleship constantly at full speed ahead for 45,000 years, while that of the Long Beach, California, earthquake in 1933 was only one-one-thousandth as strong.

**Earthquakes and Building Construction.** Buildings, particularly in regions known to be subject to earthquakes, should be built with earthquake hazard in mind. It is probably more feasible to construct buildings to withstand successfully all but rarely occurring very severe earthquakes than it is to build them against cyclones or hurricanes. Studies of earthquake effects upon buildings have made certain lessons very plain.

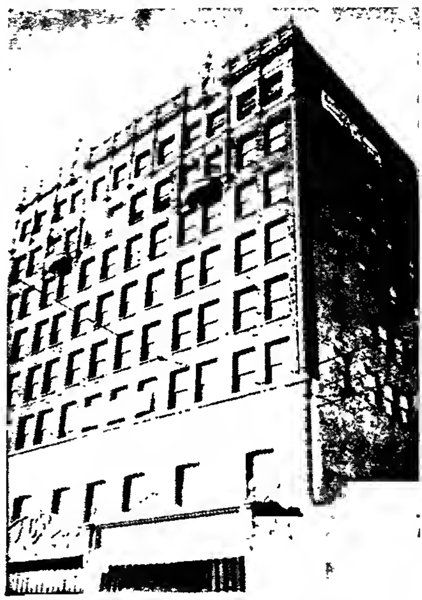


FIG. 12. A tall, well-constructed, steel-frame building practically unaffected by the Santa Barbara, California, earthquake of 1925.

Well built wooden buildings, securely anchored to good foundations, are excellent earthquake resisters and very few people are ever killed in such buildings.

Masonry buildings, as often constructed, are easily damaged or wrecked (Fig. 13). On the basis of personal observations after both the Santa Barbara and Long Beach earthquakes in California, the author is convinced that by far most of the damage to buildings involved those of ordinary masonry construction. Schoolhouses, theaters, churches, and other buildings with large rooms, and of improper masonry construction, are especially liable to damage or demolition. Masonry buildings well constructed of good materials with cross-walls or enough strong partitions, all securely tied together, are good earthquake resisters. Masonry in the auditorium type of building should be reinforced or tied by steel.

Steel-frame buildings, even skyscrapers, withstand hard shocks surprisingly well (Fig. 12). Reinforced concrete also stands well.

Buildings on made ground or loose alluvium are much more liable to damage than those on solid ground or bedrock.

In all cases careful attention should be given to foundations and

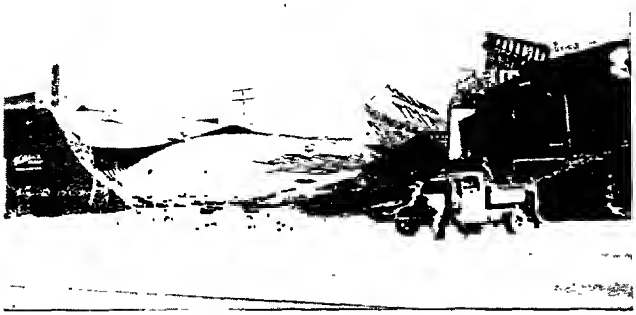


FIG. 13. Collapse of an improperly constructed masonry building during the Long Beach, California, earthquake in 1933.

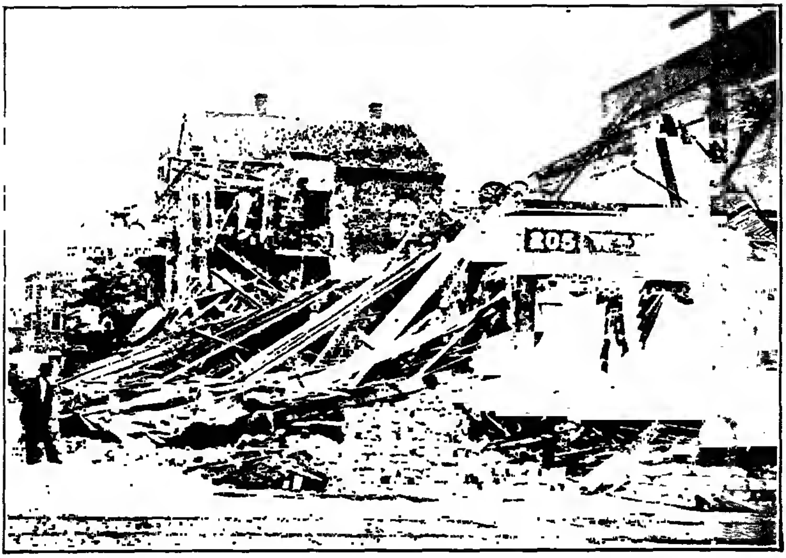


FIG. 14. Buildings wrecked by the Charleston, South Carolina, earthquake of 1886. (After Hillers, U. S. Geological Survey.)

the tieing of buildings to foundations in such manner that they can withstand a horizontal stress at least one-tenth as great as the weight of the building.

**Typical Examples of Great Earthquakes.** *Charleston, South Carolina, in 1886.* A violent earthquake shook Charleston, South Carolina, and vicinity in 1886. "A slight tremor which rattled the windows was followed a few seconds later by a roar, as of subterranean thunder, as the main shock passed beneath the city. Houses swayed to and fro, and their heaving floors overturned furniture and threw persons off their feet as, dizzy and nauseated, they rushed to the doors for safety. In 60 seconds a number of houses were completely wrecked, 14,000 chimneys were toppled over, and in all the city scarcely a building was left without serious injury (Fig. 14). In the vicinity of Charleston, railways were twisted and trains derailed. Fissures opened in the loose superficial deposits, and in places spouted water mingled with sand" (W. H. Norton). It was felt by people in places as far away as eastern Iowa, Boston, Cuba, and the Bermudas. It was caused by a rupture of the old rocks which underlie the loose Coastal Plain strata.

FIG. 15. House on the main fault wrecked at the time of the California earthquake of 1906. (Photo by R. L. Humphrey, for U. S. Geological Survey.)

*Southern Alaska in 1899.* A series of very violent earthquakes shook the Yakutat Bay region of southern Alaska in 1899 when one part of the coast rose as much as 47 feet (Fig. 2), while another part sank a little below sea level. "Vast quantities of snow and ice were avalanched from the mountains, and, as a result of this abrupt accession of supply to the reservoirs of the glaciers, a wave of advance was started which, during the succeeding years, swept down the glaciers and caused notable change and advance in the glacier ends" (Tarr and Martin). A tsunami destroyed a forest along the coast.

*California in 1906.* The California earthquake of 1906 ranks as the most violent shock recorded in the United States since the beginning of the twentieth century. The shock lasted about a minute. It caused a property damage, mainly in San Francisco, of several hundred million dollars, but fortunately the loss of life was not great. It was caused by a sudden horizontal movement of one part of the Coast Range Mountains 2 to 22 feet past the other along a line of fracture (fault) for about 250 miles (Fig. 7). Along the fracture, fences, water-pipes, houses, and roads were dislocated (Fig. 15), and the ground was torn up. In San Francisco the greatest damage by far was accomplished by fire which started in various damaged buildings and quickly spread.

*Sicily in 1908.* In regard to both violence and loss of life, the Messina, Sicily, earthquake of 1908 ranks as one of the greatest in the annals of human history. It has been estimated that between 150,000 and 200,000 people lost their lives in this frightful catastrophe which was caused by the sudden slipping of the earth's crust along a fault fracture.

*Japan in 1923.* On September 1, 1923, radio messages startled the world with news of the frightful earthquake disaster which overtook the region including Tokio and Yokohama in Japan. Earthquake and fire destroyed a large section of the great city of Tokio, and Yoko-

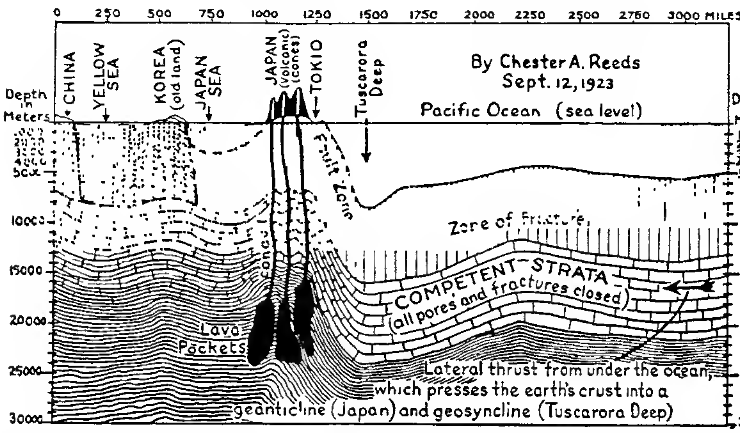



FIG. 16. Diagrammatic east-west cross section of the earth's crust in the latitude of Tokio, Japan. (After Reeds.)

hama was almost completely ruined. According to various reports, about 150,000 people were killed, and 100,000 were wounded. About 500,000 houses were destroyed, most of them by fire. The earthquake lasted five minutes. It was caused by a sudden shifting of the earth's crust, said to have been hundreds of feet, along a fault in the bottom of Sagami Bay. Parts of the shores of the bay were elevated 6 feet According to Shepard much of the change in the configuration of the bottom of the bay was due to submarine sliding seaward of large masses of soft sediment, induced by the shock, rather than to the actual dislocation of the earth's crust.

From the main island of Japan, which rises thousands of feet above sea level, there is a remarkably great and steep descent within a short distance to very deep ocean water (depth about 5 miles). This great, steep slope marks a portion of the earth's crust which is unusually lacking in equilibrium, and hence subject to rapid earth-crust movements. Accompanying Fig. 16 gives a general idea of the conditions in this great zone of unusual diastrophic activity.

# CHAPTER III

## MATERIALS OF THE EARTH—MINERALS [1]

### Definition and Significance of Minerals

Minerals are, with slight exceptions, the materials which constitute the known parts of the earth. Mineralogy is, therefore, in a very real sense the most fundamental of the various branches of the great science of geology because the events of earth-history, as interpreted by the geologist, are recorded in the mineral matter (including most rocks) of the earth. When we examine the rocky material or mineral matter of the earth in any region we find that it consists of various kinds of substances, each of which may be recognized by certain characteristics. Each definite substance (barring those of organic origin) is called a mineral. Or, more specifically, a *mineral* is a homogeneous substance of definite chemical composition found ready-made in nature and not a product of life. According to this definition, a mineral must be a natural, inorganic substance of the same nature throughout, and its composition must be so definite that it can be expressed by a chemical formula.

All artificial substances, such as laboratory and furnace products, are excluded from the category of minerals because they have taken no part in the history of the earth. Coal is not a mineral both because of its variable composition and its organic origin. A few examples of very common substances which satisfy perfectly the definition of a mineral are quartz, feldspar, mica, calcite, and magnetite. More than a thousand mineral species are known. To these, and their varieties, several thousand names have been given. Not more than forty or fifty of the many minerals are, however, of great geological importance, and of these only six or eight make up more than ninety per cent of the outer or crustal portion of the earth. Only two minerals—water and mercury—ordinarily exist in liquid form.

[1] Considerable portions of this chapter are taken by permission from Chapter XX of the present author's *The Story of Our Earth*, which forms Volume 3 of Popular Science Library published by P. F. Collier & Son Company.

## Chemical Make-up of Minerals

It is a surprising fact that of the ninety or more *chemical elements*, that is, substances which cannot be subdivided into simpler ones, only eight make up more than ninety-eight per cent of the weight of the earth's crust. It is important to note, however, that, with one very slight exception, none of the eight exists as such in mineral form. These eight elements are oxygen (nearly fifty per cent), silicon (over twenty-five per cent), aluminum (over seven per cent), iron (over five per cent), calcium (or "lime"), magnesium (or "magnesia"), sodium (or "soda"), and potassium (or "potash"). Among other elements found in useful or common minerals are carbon, hydrogen, sulphur, chlorine, fluorine, phosphorus, barium, copper, gold, lead, mercury, platinum, silver, tin, and zinc. Some of the elements last named may exist as such in nature, as for example, gold, copper, silver, carbon (in form of graphite and diamond), sulphur, and platinum.

In most cases by far two or more of the chemical elements are variously combined in such a manner (chemically) as to lose their identities as such. Thus the two vicious substances sodium and chlorine are combined to form the beneficial mineral called halite or common salt (composition, chloride of sodium). Oxygen and silicon (a gas and a solid) may be united to form the very hard, common mineral called quartz (composition, oxide of silicon). Three elements—calcium, carbon, and oxygen—are united in the common mineral known as calcite (composition, carbonate of lime). Four elements—potassium, aluminum, silicon, and oxygen—are chemically combined in the exceedingly common mineral known as orthoclase feldspar (composition, potassium aluminum silicate). Some other minerals are still more complicated in composition.

## Geological Importance of Minerals

Certain rock formations are made up essentially of but one mineral in the form of numerous individual grains, as for example pure limestone which may consist wholly of calcite (carbonate of lime), or pure sandstone which may contain only grains of quartz (oxide of silicon). Most of the ordinary rocks are, however, made up of two or more minerals mechanically bound together. Thus, in a specimen of granite on the author's desk, several distinct mineral species are distinguishable by the naked eye. These mineral grains are from one to five millimeters across. Most common among them are hard, clear, glassy grains,

called quartz; nearly white, hard grains, often with smooth faces, called feldspar; small, silvery white flakes, called mica; and small, hard, black grains, called magnetite.

It is the business of the mineralogist to learn the characters of each mineral, how they may be distinguished from each other, how they may be classified, how they are found in nature, how they originate, and what economic value they may have. It is an important part of the business of the geologist to learn what individual minerals combine to form the various kinds of rocks (described in Chapter IV), how such rocks originate, what changes they have undergone, and what geological history they record. It is thus clear that mineralogy is an important part of geology, which latter is essentially the science of rocks.

## Crystal Forms of Minerals

One of the most remarkable facts about minerals is that most of them by far have a crystalline structure, that is, they are built up of definitely arranged tiny particles known as molecules. Crystalline min-

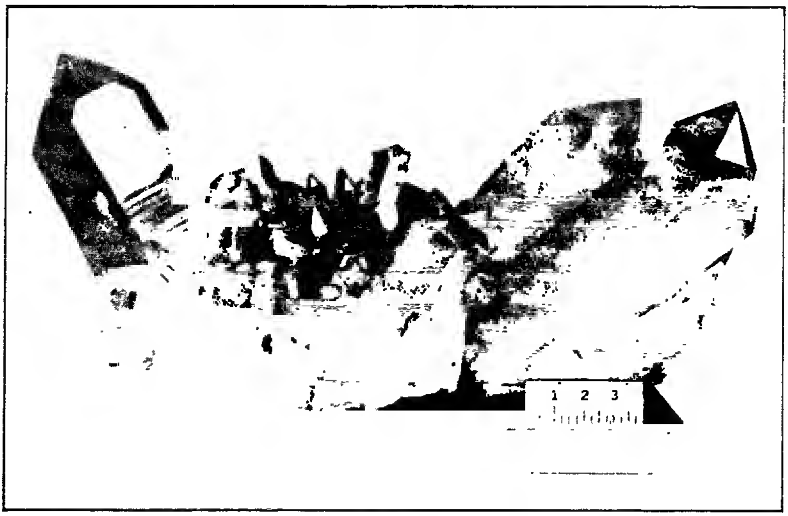



Fig. 17. A group of quartz crystals. (Courtesy of the American Museum of Natural History.)

erals are often more or less regular, solid forms bounded by plane faces and sharp angles, such forms being known as *crystals* (Fig. 17). How do crystals develop such regularity of form? Any solid is considered to be made up of many very tiny (sub-microscopic) molecules held

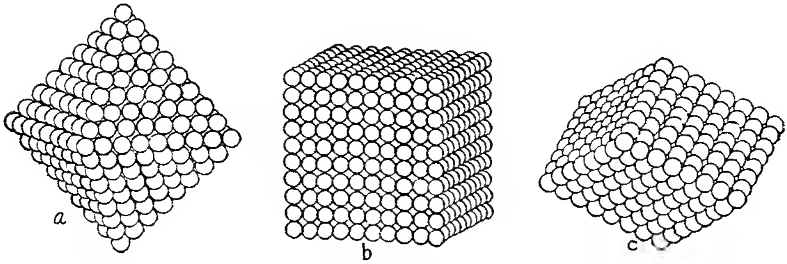



FIG. 18. Piles of shot illustrating the molecular structure of crystals. (After Whitlock, New York State Museum.)

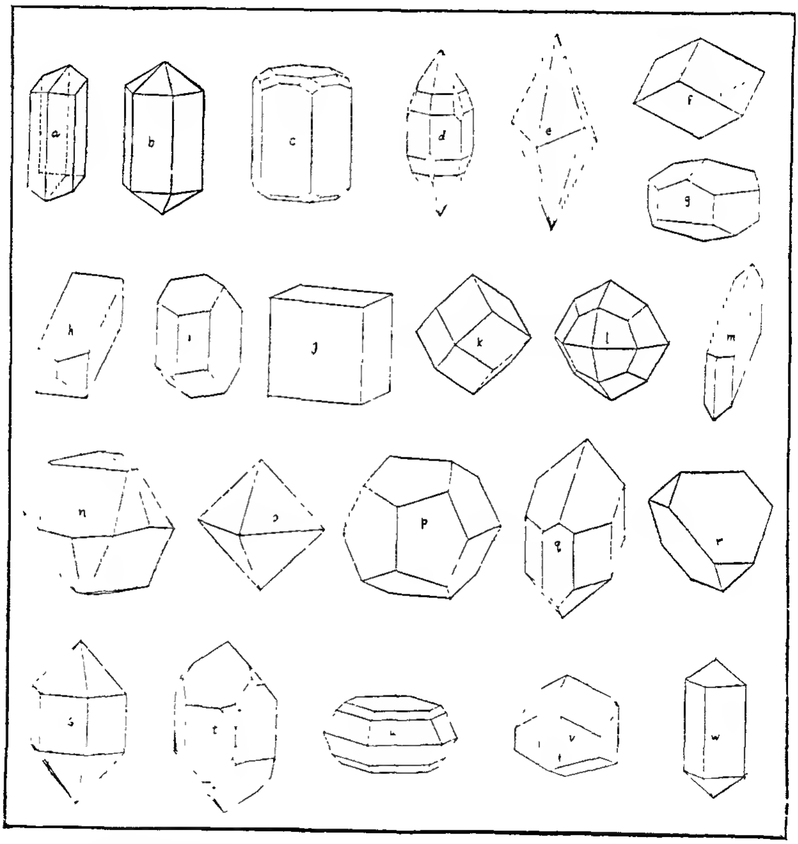



FIG. 19. Crystal forms of some common minerals: *a*, amphibole; *b*, apatite; *c*, beryl; *d*, corundum; *e*, *f*, *g*, calcite; *h*, *i*, feldspar; *j*, fluorite; *k*, *l*, garnet; *m*, gypsum; *n*, hematite; *o*, magnetite; *p*, pyrite; *q*, pyroxene; *r*, chalcopyrite; *s*, *t*, quartz; *u*, sulphur; *v*, tourmaline; *w*, zircon. (After New York State Museum.)

together by an attractive force called cohesion. In liquids the molecules may more or less freely roll over each other, thus altering the shape of the mass without disrupting it. In gases the molecules are considered to be relatively long distances apart and moving rapidly. During the process of change of a substance from the condition of a liquid or a gas to that of a solid, due to lowering of temperature or evaporation, the cohesive force pulls the particles (molecules) together into a rigid mass. Under favorable conditions such a solid possesses a regular polyhedral form.


FIG. 20. Part of a crystal of calcite showing three well-developed cleavages.

The process of crystallization has been clearly suggested by Whitlock who says: "This results from the fact that particles or molecules of the substance which, while it was liquid or gaseous, rolled about on one another, have been in some way arranged, grouped, and built up. To illustrate this, suppose a quantity of small shot to be poured into a glass: the shot will represent the molecules of a substance in a liquid state, as for example a solution of alum. If, now, we suppose these same shot to be coated with varnish or glue so that they will adhere to each other, and imagine them grouped as shown in Figure 18a, they will represent the arrangement of the molecules of the alum after it has become solid or crystallized. This arranging, grouping, and piling up of molecules is called *crystallization*, and the solid formed in this way is called a *crystal*. Figures 18b and 18c show the shot arranged to reproduce two common forms of crystals (e.g. fluorite and calcite)."

Certain facts furnish all but absolute proof of regularity of arrangement of particles within crystals. Among these facts are the wonderful regularity (*symmetry*) of faces upon crystals; the remarkable property

of most crystals to split (cleave) readily in certain directions: the grouping of crystals according to characteristic effects of the passage of light (especially of polarized light) through them; and x-ray photographs showing systematical arrangement of groups of particles within crystals.

All crystals may be grouped into seven systems, each characterized by a certain type of arrangement of crystal faces, angles, and edges about imaginary lines (axes) which run through the center of the crystal. Each system contains from two to seven classes of symmetry, there being thirty-two in all. Each class contains seven fundamental crystal forms. Thus, two of the seven fundamental forms of the class to which garnet belongs are represented by Figures 19k and 19l. Figure 19 illustrates perfect crystal forms of a number of common and useful minerals.

## Physical Properties of Minerals

**Cleavage.** Many crystals and crystalline substances exhibit the important property known as *cleavage*, that is, a marked tendency to break or split easily in certain well-defined directions yielding more or less smooth surfaces. A cleavage surface is, as would be expected, always parallel to an actual, or at least a possible, crystal face, because the splitting occurs along planes of weaker molecular cohesion. The degree of cleavage varies from almost perfect, as in mica, to very poor or none at all, as in quartz. The number of cleavage directions exhibited by common minerals is illustrated by the following: mica, one; feldspar and amphibole, two; calcite (Fig. 20) and galena, three; fluorite, four; and sphalerite, six. In the study of mineral specimens, careful attention should be given to cleavage whenever it occurs, for certain minerals always show certain cleavage directions.

**Hardness.** An important criterion for the recognition of minerals is *hardness*, by which is meant the degree of resistance which a smooth mineral surface offers to abrasion or scratching. Scarcely any two minerals are just alike in hardness, but for practical purposes a generally adopted scale recognizes ten degrees of hardness as follows:

1. Soft, greasy feel, and easily scratched by the finger nail (e.g. talc).
2. Just scratched by the finger nail (e.g. gypsum).

3. Just scratched by a copper coin (e.g. calcite).
4. Easily scratched by a knife, but does not scratch glass (e.g. fluorite).
5. Just scratches common glass, and is scratched by a knife (e.g. apatite).
6. Not scratched by a knife and scratches common glass easily (e.g. orthoclase feldspar).
7. Much harder than steel, and scratches hard glass easily (e.g. quartz).
8, 9 and 10. Harder than any ordinary substance, and represented in order by topaz, corundum, and diamond.

**Color.** Minerals show a great variety of colors. Many of them, like pure quartz, gypsum, halite, and calcite, are colorless or white. Many of them, like galena (steel-gray), pyrite (brass-yellow), azurite (blue), malachite (green), magnetite (black), and cinnabar (red), possess these colors as inherent characteristics which never fail. Still others, like amethyst (purple) and sapphire (blue) are colored by impurities.

**Lustre.** *Lustre* is the appearance of the surface of the mineral independent of the color. It is often more or less characteristic of a mineral such as metallic, glassy, resinous, greasy, dull, brilliant, etc.

**Transparency.** A mineral is said to be transparent when an object can be seen clearly through it; translucent when it transmits light but an object cannot be seen through it; and opaque when it transmits no light.

**Streak.** Certain of the colored minerals are colored differently when in powdered form. A simple way to get a little of the powdered mineral is to rub the specimen on a piece of unglazed porcelain (so-called "streak-plate"). The *streak* so obtained may be characteristic of the mineral, and this greatly aids in identifying the species. Thus, black hematite gives a red streak; black limonite a yellowish brown streak; yellow pyrite a greenish black streak; etc.

**Weight.** Minerals vary greatly in weight, each one having its own characteristic specific gravity, that is, weight in proportion to that of an equal volume of water. The range is from less than 1 to about 23. The average specific gravity of all minerals is about 2.6. It is important to note the relative weight of the specimen examined because it often aids in recognizing the species.

## Some Examples of Common Minerals

A number of important characteristics of each of the following common minerals are listed, and the reader should study them with good specimens before him for examination. In this way the properties of minerals in general will be much better understood.

**Quartz.** Composition, silicon dioxide. Crystals, usually six-sided prisms capped by six-sided pyramids. Cleavage, practically none. Colorless or white when pure. Hardness, 7. Specific gravity, 2.6. (See Figs. 17 and 19s, t).

FIG. 21. A group of feldspar (microline) crystals.

**Calcite.** Composition, carbonate of calcium. Crystals have faces arranged in sixes or threes around an axis (Fig. 19e, f, g). Cleavage, very good in three directions, none at right angles. Colorless or white when pure. Hardness, 3. Specific gravity, 2.7.

**Gypsum.** Composition, a compound of calcium, sulphur, and oxygen containing water in combination. $CaSO_4 \cdot 2H_2O$. Crystals, usually tabular prismatic (Fig. 19m). Colorless or white when pure. Transparent to opaque. Hardness, 2, and easily scratched by the finger nail. Specific gravity, 2.3. Three good cleavages crossing at angles of 66° and 114°.

**Feldspars.** Composition, silicate of aluminum and potassium (orthoclase variety) or sodium-calcium (plagioclase variety). The several kinds have common properties as follows: Crystals have prismatic faces meeting at or near 90° or 120°. Color, white, gray, or pink. Cleavage, two good ones at or near 90°. Hardness, about 6. Specific gravity, about 2.6. (See Figs. 21 and 19h, i).

**Micas.** Composition, silicate of aluminum with potassium, magnesium, etc. Crystals, usually six-sided plates. Cleavage, excellent in one

direction. Colorless, black, brown, etc. Muscovite is a colorless variety, and biotite is black. Hardness, 2 to 2.5. Specific gravity, 2.7 to 3.

**Amphiboles.** A number of species related in composition, crystal form, and properties are here included. They are mostly very complicated compounds of silicon, oxygen, lime, and magnesia, usually also with aluminum and iron. The most common and important one is called *hornblende*. It crystallizes with well-defined prismatic faces (Fig. 19a), and with two good cleavages crossing at angles of about

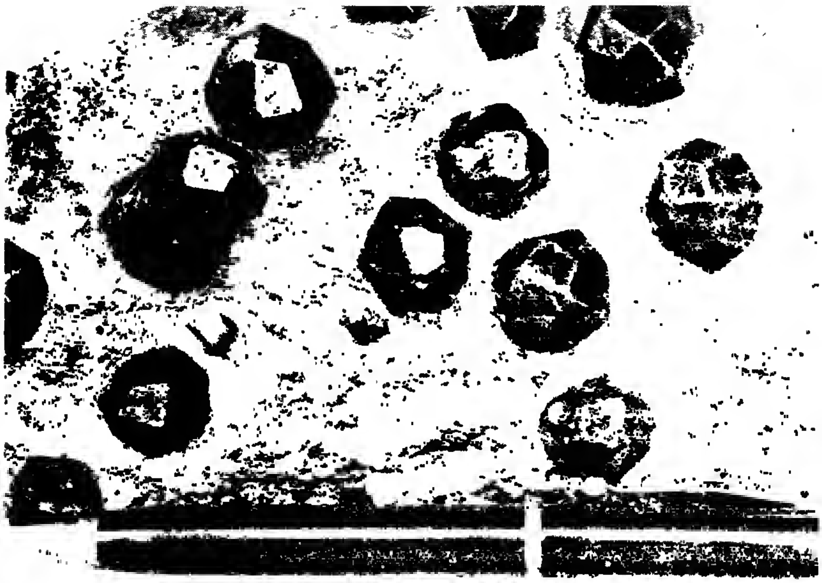


FIG. 22. Garnet crystals in schist.

124° and 56° and parallel to the prismatic faces. Color, dark brown to black. Transparent to opaque. Hardness, nearly 6. Specific gravity, over 3.

**Pyroxenes.** Composition, complicated silicate of aluminum with various other elements producing several varieties. Crystals, prismatic forms with alternate faces meeting at nearly 90° (Fig. 19q). Cleavage, two fairly good ones at nearly 90°. Color, usually black, but may be white, green, or brown, according to variety. Hardness, 5 to 6. Specific gravity, 3.2 to 3.6. Augite is the most important variety. It is dark green, brown, or black.

**Garnets.** Composition, a silicate, usually of aluminum, and either lime, magnesia, or iron. Crystals, 12 or 24 faces, or a combination of the two (Figs. 19k. l, and 22). Cleavage, very poor. Color, variable, but mostly red, brown, black, or green. Hardness, 6.5 to 7.5, and specific gravity, 3.1 to 4.3, each varying according to composition and variety.

**Pyrite.** Composition, sulphide of iron. Crystals, usually cubes or twelve-faced, each face of the latter being a pentagon (Fig. 19p). Cleavage, none. Color, brass yellow. Luster, metallic. Hardness, 6. Specific gravity, 5.

**Magnetite.** Composition, an oxide of iron. Crystals, usually octahedrons. Cleavage, none. Color, black. Luster, metallic. Highly magnetic. Hardness, 6. Specific gravity, 5.

**Hematite.** Composition, combination of iron and oxygen. $Fe_2O_3$. Crystallizes in rather complex six-sided forms (Fig. 19n). Often in rounded masses. Color when crystalline is black with metallic luster, otherwise it is dull red. Opaque. Streak is always red. No cleavage. Hardness, about 6. Specific gravity, about 5.

**Galena.** Composition, sulphide of lead. Crystals, usually cubes. Cleavage, good in three directions at right angles to each other. Color, lead gray. Luster, metallic. Hardness, 2.5. Specific gravity, 7.5.

**Graphite.** Composition, carbon. Crystals, usually six-sided plates. Cleavage, good in one direction. Color, black. Luster, metallic. Feel, greasy. Hardness, about 1.5. Specific gravity, 2.2.

## CHAPTER IV

# MATERIALS OF THE EARTH—ROCKS

### Introduction

**Definitions.** The solid portion of the earth, or lithosphere, is, as far as known, composed of mineral and rock material. A *rock* may be defined as an aggregate of minerals if we use the term "mineral" in a loose sense to include exceptional material like coal. It is most common by far for a rock to contain two or more mineral species, but in some cases it may consist mainly, or wholly, of one mineral species, such as beds of gypsum, salt, many limestones, and certain iron ores. A rock very often consists of 5 to 10, or more, minerals. Solidity and hardness are not necessary features of rocks, for deposits of loose sand and soft clay are rocks just as truly as the hardest sandstone or granite. A *rock formation* is a more or less extensive constituent of the earth's crust, exhibiting rather characteristic features throughout. *Petrology* is the study of rocks.

**Three Great Groups of Rocks.** Broadly considered all rocks may be classified in three great groups as follows:

I. *Sedimentary rocks*, comprising all earth materials deposited by water, wind, ice, and organic agencies. Examples, sandstone and limestone.

II. *Igneous rocks*, comprising all earth materials which were once in a molten condition. Examples, lava and granite.

III. *Metamorphic rocks*, comprising all profoundly altered (metamorphosed) sedimentary and igneous rocks. Examples, schist and slate.

**General Significance of Rocks.** The science of geology is based largely upon the study of rocks, particularly in regard to their origin and history; the forces of nature which affect them; and the events of earth history which they record. It is, therefore, important that the student of geology should early gain at least an elementary knowledge of the more common kinds of rocks. Only by a knowledge of the nature of the materials of the lithosphere (mostly rocks) can the action of geological processes upon them be rightly understood. To this end the student should supplement his reading with study of specimens in

the laboratory, and of actual rock exposures in the field, as far as that may be feasible.

## SEDIMENTARY ROCKS

**General Characteristics.** Rock and mineral matter of any kind carried by water, wind, or ice becomes *sediment*, which, in the course of time, is deposited as such. Most sedimentary rocks by far originate as sediments. One of the most common characteristics of such sedimentary rocks is their division into layers, i.e. their *stratification* (Fig. 23). By throwing a quantity of loose rock material, the fragments of which range from very fine to coarse, into standing water, the

FIG. 23. An outcrop showing excellent stratification or bedding. The beds of sandstone (light gray) and thinner (darker) beds of shale have been tilted out of their original horizontal position. Near Oxnard, California.

coarsest material would settle first, and upon it successively finer and finer material. There would be a gradation from the coarsest material at the bottom to the finest at the top. By repeating the process a similar *layer* (or *bed*) would accumulate on top of the first, and the two layers would be separated rather sharply by a *stratification* or *bedding surface*. In water with a current there would be a tendency toward horizontal as well as vertical gradation of the sediment in each layer or bed due to the sorting power of the running water. The term *stratum* (plural,

*strata*), strictly speaking, applies to a collection of successive beds or layers of the same sort of rock material, but is very often used in the same sense as *bed* or *layer*. It should be borne in mind that some sedimentary rocks show little or no sign of stratification, as for example in the case of many glacial deposits. Wind deposits are often more or less crudely stratified.

Another common characteristic of many sedimentary rocks is the rounded nature of the fragments and particles which compose them. This is due to the fact that any sharp angles of rock and mineral fragments tend to be worn away by abrasion during transportation by water, wind, or glaciers. This feature stands in sharp contrast with that of the typical igneous rocks which are masses of more or less angular minerals (or crystals).

FIG. 24. An outcrop of sandstone showing a thick bed below and thin beds above. Near Johnstown, New York.

Sedimentary rocks often contain *fossils* (Fig. 27), that is, remains or impressions of animals and plants, while igneous rocks by their very nature almost never do.

**Where Sediments are Deposited.** The greatest theatre of sedimentation is the sea. The general tendency is, and has been for long ages, for the land waste, resulting from disintegration and decay of rocks, to be carried into the sea, very largely by rivers. Most of this

sediment, amounting to vast quantities each year, is deposited in the shallow water relatively near the land, that is, within 100 to 200 miles of the shore. Shells and remains of various animals and plants, as well as volcanic materials (especially dust), accumulate over vast areas of the sea floor. Large quantities of material worn from the shores by wave action are also deposited in the sea.

Most lake bottoms receive sediments both derived by wave action and carried in by streams. Mineral matter in solution, such as salt and gypsum, may also be precipitated during evaporation of lake water.

FIG. 25. A specimen of conglomerate showing water-worn pebbles.

More or less deposition of the tremendous amount of sediment carried by streams takes place along the stream courses, particularly on their flood plains, or where streams emerging from mountains flow out into deserts and dry away.

Vegetable matter, which in many places may be changed into coal, accumulates in swamps, bogs, and some lakes.

Various types of sediments are deposited directly upon the land. Thus piles of rock fragments derived from cliffs often accumulate at their bases; wind, especially in desert regions, transports and deposits great quantities of dust and sand; mineral-charged waters (springs) emerging from the earth deposit their mineral matter at the surface; and glaciers transport and deposit large amounts of rock waste directly upon the land.

**How Sediments are Consolidated.** Most sedimentary rocks are now consolidated into relatively hard rocks, but at the time of their deposition they were mostly loose, incoherent masses. Thus the familiar rock known as sandstone was once loose sand, and shale was formerly soft mud. What causes the consolidation of sediments? One important factor is *weight* or *downward pressure*. Where strata pile up to

thicknesses of many hundreds, or even thousands, of feet as they commonly do, the weight or downward pressure of the overlying masses tends to squeeze together the fragments and particles of the lower masses of the pile, causing them to consolidate, perhaps by adhesion and cohesion.

*Cementation* is another important cause of consolidation of sediments. Waters penetrating the earth's crust carry various minerals in solution, and at considerable depths such minerals are deposited in the spaces of the loose sediment, causing the whole mass to be tightly bound together.

Consolidation may also be effected by *heat*. The source of the heat may be bodies of molten material which rise locally into masses of strata, or it may be the general interior heat of the earth where the bottom portions of thick piles of strata are far enough down to become appreciably affected.

Mention may be made also of the influence of *lateral pressure* in the consolidation of sediments. Such a pressure may be exerted upon a great body of strata, causing it to be crumpled and raised into a mountain range as explained in Chapter XIII.

**Kinds of Sedimentary Rocks.** The more common kinds of sedimentary rocks may be classified in a general way as follows:

PRINCIPAL KINDS OF SEDIMENTARY ROCKS

| | |
|---|---|
| 1. Mechanical or fragmental origin. | Sands and sandstones.<br>Gravels and conglomerates.<br>Clays and shales.<br>Loess.<br>Talus and breccias. |
| 2. Chemical origin. | Salt and gypsum.<br>Some limestones.<br>Travertine and siliceous sinter.<br>Bog iron-ore. |
| 3. Organic origin. | Most limestones, including chalk.<br>Diatomaceous earth.<br>Peat, lignite, and coal. |

*Sedimentary rocks of mechanical origin.* The sedimentary rocks classified in this category are of mechanical origin, and they consist largely or wholly of fragments of preexisting rocks carried along and deposited by water, wind, or ice. They are known as *clastic rocks.*

*Sands* are incoherent masses of fine, more or less rounded grains

of mineral or rock fragments, usually consisting mainly of quartz. The grains are not more than a few millimeters in diameter.

*Sandstones* are consolidated sands of varying degrees of hardness. The grains of sand are generally held together by a cement such as lime, oxide of iron, or oxide of silicon (silica), etc. Sandstones are generally stratified in layers varying from thin to thick (Fig. 24). They vary greatly in color according to the nature of the fragments, cementing material, and impurities which they contain. They are most often white, gray, brown, or red. Sandstones are usually very porous because of the numerous, relatively large spaces between the grains of the rock. There are many more or less impure varieties of sandstone, as for examples *calcareous sandstone*, containing much lime; *micaceous sandstone*, containing many flakes of mica; *argillaceous sandstone*, rich in clay; and *arkosic sandstone*, rich in fragments of feldspar.

*Gravels* are incoherent masses of more or less rounded pebbles of any kind of rock ranging in size from a few millimeters to boulders a foot or more in diameter. The most common pebbles are of quartz, not only because this mineral is so abundant, but also because it is so hard that the rolling and rubbing action of water, wind, or ice often only rounds off pebbles of it, while softer minerals and rocks are reduced to fine materials.

*Conglomerates* are masses of gravel cemented together (Fig. 25). They are usually much more crudely stratified than sandstones because of the conditions under which they are deposited. They are given various names according to the prevailing kinds of pebbles in them, as *quartz conglomerate*, *granite conglomerate*, *limestone conglomerate*, etc.

*Clays* consist of very finely divided, decomposed rock and mineral matter of various kinds, but usually mostly of kaolin. They are plastic when moist. *Muds* are made up of very finely divided, little decomposed or fresh rock and mineral fragments of various kinds. They show little or no plasticity when moist. *Shales* are consolidated clays and muds. Clays, muds, and shales commonly vary in color from white through gray to black, and from bluish-gray or yellow through brown to red, the latter colors usually being due to the presence of an iron compound of some kind. Dark gray to black clays and shales usually owe their color to the presence of considerable decomposing organic matter, as for example *carbonaceous shale*. A limy clay is usually called *marl*. There are also *sandy shales*, containing considerable sandy material, and *calcareous shales*, containing more or less limy material. Shales and clays are usually well stratified, often in thin layers (Fig. 26).

Thin-bedded shales may be readily split into thin plates parallel to the stratification.

*Loess* is a very fine grained, usually buff colored sandy, often limy, clay, mainly of wind-blown origin.

*Talus* is a mass of more or less angular, loose fragments of rock of any kind that accumulates at the base of a cliff or steep slope (Fig. 46). *Breccias* are masses of more or less angular rock fragments which have been cemented together.

*Sedimentary rocks of chemical origin.* In this category are included

FIG. 26. A large outcrop of strongly tilted, evenly stratified shales. Total thickness of the beds is hundreds of feet. Piru Canyon on the Ridge Road, Los Angeles County, California.

all sedimentary rocks which have been formed by deposition (or precipitation) of mineral matter from solution.

*Salt* and *gypsum* are precipitated from salt lakes and lagoons which are subject to excessive evaporation, that is, where evaporation balances or exceeds inflow of water. The tendency is thus for the mineral matter to accumulate in solution until the point of saturation is reached, after which precipitation results. If both salt and gypsum are in solution the gypsum is deposited first because it is less soluble than the salt. Extensive deposits of both of these minerals exist in many regions, and

they are usually well stratified. When pure they are white, but they are often variously colored by impurities.

Where lime is in solution in lakes or lagoons, excessive evaporation may lead to its deposition, thus forming limestone. Such limestone is, however, far less common than that of organic origin described beyond.

*Travertine* and *siliceous sinter* are more or less porous, usually white, spring deposits, being especially conspicuous around the mouths of hot springs. They are both remarkably well developed in Yellowstone Park, the former at Mammoth Hot Springs, and the latter around the geysers.

FIG. 27. A specimen of shell limestone many millions of years old.

Travertine consists of limy material which bubbles when touched with hydrochloric acid, and siliceous sinter consists of silica, that is, a compound of silicon and oxygen which is not affected by the acid.

*Bog iron-ore* precipitates on the floors of certain bogs or lakes when an iron compound in solution in the water becomes oxidized, and therefore insoluble.

*Sedimentary rocks of organic origin.* Most *limestones* consist of the limy shells, or fragments of shells, or other limy remains of animals and plants, mostly of animals. In many cases the organic remains, or at least fragments of them, are obvious to the naked eye (Fig. 27). In some cases such material can be made out only under a hand lens or

microscope. In still other cases the limy organic remains either have been so thoroughly ground up (e.g. by waves on coral beaches), or so completely altered by crystallization, that the original organic structures are wholly obscured. Most of the great, very extensive limestone formations have formed on the sea floor by accumulation of limy shells, etc. Limestones are usually well stratified (Fig. 28).

*Chalk* is a very fine grained, soft limestone with an earthly texture. It is usually white to light gray. Much chalk consists of the tiny shells of single-celled organisms such as coccolithophores. Limestones are often impure due to a mixture with more or less sandy or clayey material, etc., and become *sandy limestones, clayey* (or *argillaceous*) *limestones,* etc. *Shell marl* is clayey material rich in limy shells or fragments of shells. All rocks here described under the category of limestones bubble when treated with ordinary acid. They are usually well stratified.

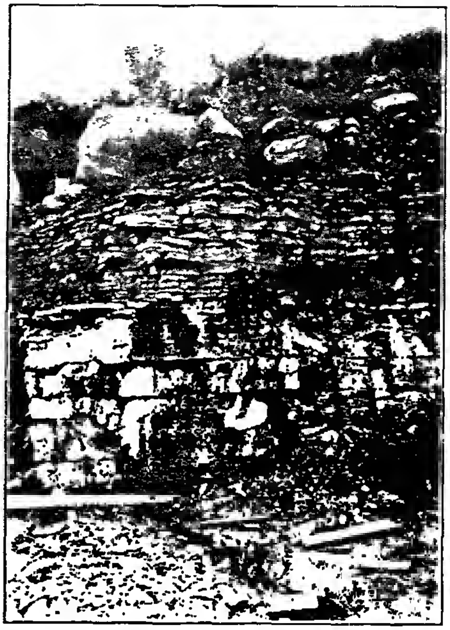


FIG. 28. An outcrop of limestone, distinctly bedded. Glacial boulders on top.

*Diatomaceous earth,* or diatomite, is soft, very fine grained, usually white or gray, earthy material composed mainly or wholly of the siliceous shells or secretions of minute, single-celled plants called diatoms. It is usually well stratified, often in exceedingly thin layers when it is sometimes called diatomaceous shale. It looks much like chalk, but acid does not affect it.

*Peat, lignite,* and *coal* all represent accumulations of beds of vegetable matter, usually under swamp conditions, which have been more or less decomposed (or carbonized). Vegetable matter of this kind, when only slightly altered, is called peat; when it is somewhat more decomposed it is called lignite (an imperfect coal); and when it is very much changed under conditions of burial in the earth, so that the percentage

of carbon is relatively high, it is called coal, including both bituminous and anthracite coal. Coal is more or less well stratified, and it usually forms beds between beds of shale or sandstone.

**Special Features of Strata.** *Ripple marks.* These are small parallel ridges, seldom more than a few inches high, formed by the rippling action of either water or wind on certain incoherent sediments, especially sands and sandy materials in general. They are particularly characteristic of the action of waves in shallow water. A ripple-marked surface may be hardened enough to be deeply buried under other strata, and later exposed by removal of the overlying strata by a natural process (erosion). Figure 29 shows ripple marks of this kind millions of years old. Ripple marks are also made by wind action on wind-blown deposits, particularly on sand dunes (Fig. 146).

Fig. 29. Ancient ripple-marked sandstone.

*Mud cracks.* When soft mud or sandy mud is left exposed to the air after withdrawal of high water, the material dries and cracks into a network of fissures. Flood plains of rivers and desert basins, with their alternating wet and dry surfaces, are often very favorable for their development. During dry weather such a cracked surface hardens, and the fissures may either be filled with wind-blown dust or sand, or the next flood may first fill the cracks, and then cover the surface with coarser sediment. Thus a mud-cracked surface may, in the course of time, be deeply buried below the surface, and later exposed by wearing away of the land.

*Cross-bedding.* This is irregular bedding at various angles to the general planes of stratification of a formation (Fig. 31). It is caused by the action of tides or water or wind currents varying notably in force or direction. Rapid, shifting currents in shallow water of rivers, lakes, and even the sea, favor its development. Wind-blown deposits are also often cross-bedded because of the shifting conditions of deposition.

*Fossils.* Stratified rocks very often contain remains or impressions of animals and plants of former geologic ages. Sediments which were

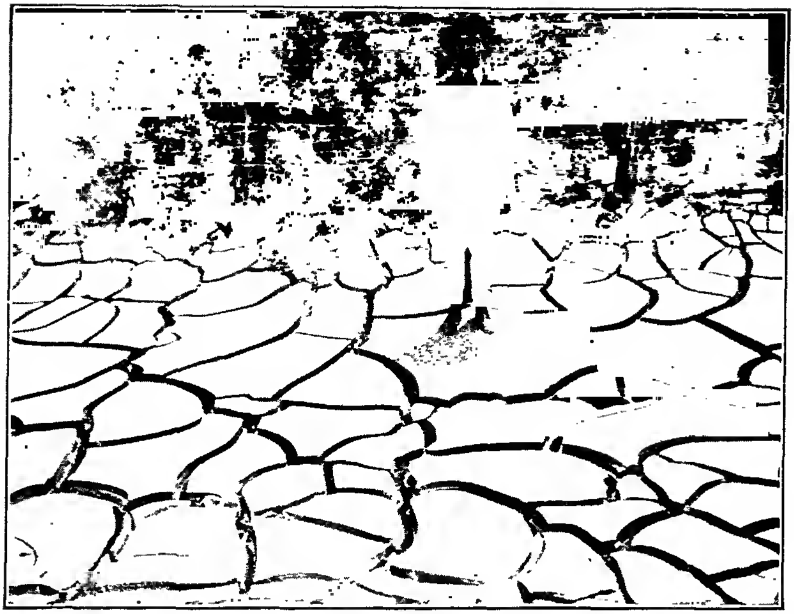


FIG. 30. Mud cracks in a desert, near Cedar City, Utah.

FIG. 31. Cross-bedded sandstone. Near Kanab, Utah. (Photo by D. W. Johnson.)

deposited in the sea are, as a rule, richest in such fossils (Fig. 27). Lake and river deposits also often contain fossils, and sediments accumulated on land sometimes do. Even occasional tracks of land and water animals of millions of years ago are wonderfully preserved.

*Concretions or nodules.* These are rounded or irregular masses of material differing in kind and rather sharply separated from the beds or strata in which they occur, and harder than the latter. They are found in a great variety of shapes, sometimes suggesting fossil forms.

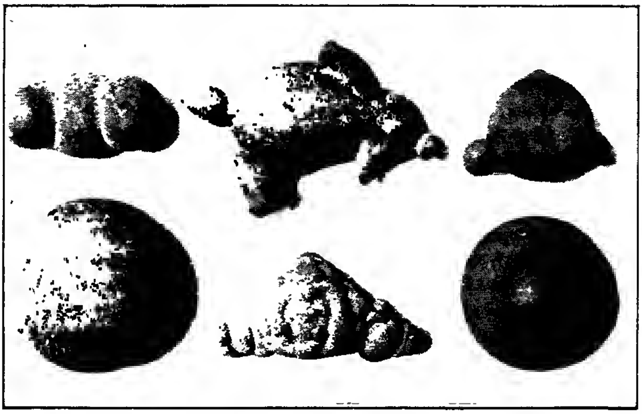


FIG. 32. Concretions from clay beds of the Connecticut Valley, Massachusetts. One-half natural size.

Some small ones are shown in Fig. 32. They range in diameter from less than an inch to a number of feet or yards. They are not pebbles or boulders deposited along with the sediments which contain them as proved by the fact that stratification surfaces often pass right through them. They are segregations, possibly aided by some crystallization, of certain materials, often around some object like a shell or leaf, formed either during or after the consolidation of the sediment. Their precise mode of origin is, however, not known.

## IGNEOUS ROCKS

**General Characteristics.** Igneous rocks are usually massive as compared to the generally stratified character of the sedimentary rocks. In some places, as with lava-flows (Fig. 167), igneous rocks may be piled up in layers, but such rocks can, by their other characteristics, be told from stratified rocks. Among such other characteristics of

igneous rocks are the general uniformity of appearance of masses or layers for considerable distances, both vertically and horizontally; the usual angular, instead of rounded, shapes of many, or all, of the mineral constituents; the peculiar texture, especially the interlocking of the minerals; their mode of occurrence, especially where they cut across other rocks; the effects of their heat upon adjacent rocks; and their almost utter lack of fossils.

**Magma and Its Consolidation.** Molten material which has its origin within the earth is called *magma*. Solidification of magma produces igneous rock. Magma may be regarded as a very hot solution (1500° to 2500° F.) of certain substances dissolved in others. Some

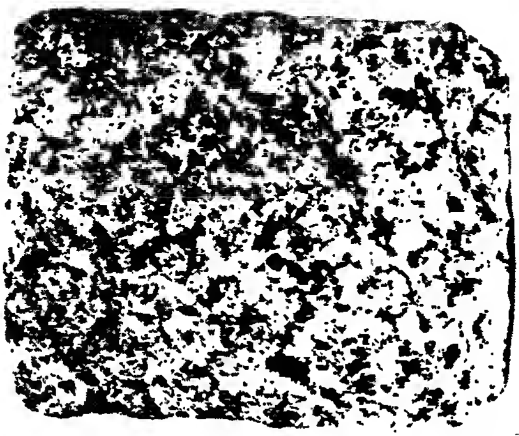


FIG. 33. A specimen of granite showing a granitoid texture. Two-thirds natural size.

of these substances are volatile (gaseous), such as water vapor or steam, carbon dioxide, and sulphurous gases, while others are nonvolatile, mainly oxides of silicon, aluminum, iron, calcium, magnesium, potassium, and sodium. These oxides, partly as such, but mostly in numerous combinations, involving two or more of them, produce the minerals of igneous rocks. The volatile materials, however, enter but little into the composition of the minerals. The relative amounts of the magmatic substances vary greatly, and hence the igneous rocks produced from magmas show wide differences in chemical and mineral composition.

When hot magma under great pressure within the earth moves upward into the earth's crust, or to the surface, both pressure and temperature are lowered. Pressure reduction allows the contained gases to

escape either into the adjacent rocks within the earth or through volcanoes, often explosively. With a sufficiently slow lowering of temperature, a time comes when some of the nonvolatile constituents of the magma begin to grow into mineral crystals by systematic arrangement of the molecules. Finally the whole mass becomes a solid pack of variously oriented crystals, including a number of different kinds (Fig. 33). Due to much interference with each other during their growth, crystal faces are usually not well defined. Under conditions of very slow cooling, the magma remains highly fluid long enough for the molecules to move freely so that fewer crystal centers originate and the rock will, therefore, be comparatively coarse grained. Very fast cooling causes the magma to become so viscous that the molecules cannot arrange themselves into crystals, and so the rock becomes glassy. The cooling may be at such a rate that many local centers of crystallization develop and the rock becomes fine grained.

FIG. 34. A specimen of lava showing a porphyritic texture. Two-thirds natural size.

**Textures and Minerals of Igneous Rocks.** The texture of an igneous rock refers to its appearance when examined in detail. It involves mostly the shapes, manner of aggregation, and relative sizes of the mineral constituents.

When most of the mineral grains or crystals making up the rock are of approximately uniform size, and readily visible to the naked eye, the rock is said to have a *granitoid texture* (Fig. 33).

When the rock contains many mineral grains too small to be made out by the naked eye, it is said to have a *felsitic (or compact) texture.* Such a rock may be partly uncrystallized.

Igneous rocks with relatively large crystals, often with good crystal outlines, embedded in a distinctly finer grained or glassy groundmass are said to have a *porphyritic texture* (Fig. 34). Such a texture indicates two distinct stages of crystallization.

When a magma cools and solidifies very rapidly with practically no crystallization a *glassy texture* results (Fig. 35).


FIG. 35. A specimen of obsidian (volcanic glass). Two-thirds natural size.

Escape of gases and steam through the upper portion of a lava-flow may fill it with bubbles so that on cooling it has a *cellular texture*.

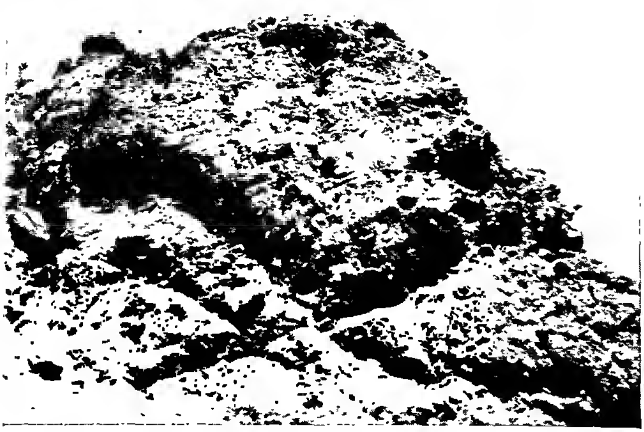


FIG. 36. An outcrop of volcanic breccia showing a coarse fragmental texture. Ten miles west of Reno, Nevada.

The term *fragmental texture* may be applied to an accumulation (loose or consolidated) of fragments of igneous rocks which have been explosively ejected from volcanoes (Fig. 36).

Scores of mineral species are known to occur in igneous rocks, but comparatively few of them are abundant. Most common of all are feldspars (both orthoclase and plagioclase), quartz, micas, pyroxenes, amphiboles, magnetite, and olivine. Small amounts of pyrite, apatite, and zircon very commonly occur.

**Plutonic and Volcanic Igneous Rocks.** In regard to modes of occurrence of igneous rocks, there are two main types, the *plutonic* or *intrusive* and the *volcanic* or *extrusive*. The former type results from cooling of magma which has been forced into the crust of the earth, but not to its surface, for example, granite. Such rock is now visible only because of removal of the overlying material by natural agencies. The latter (volcanic) type results either from solidification of magma which pours out on the earth's surface (e.g. lava-flows), or from accumulation of igneous rock fragments which are thrown out by explosive action of volcanoes (Fig. 36). The modes of occurrence of igneous rocks are considered toward the end of Chapter VI.

**Kinds of Igneous Rocks.** The principal kinds of igneous rocks may be classified in a general way on the basis of essential mineral content and texture. In the study of the table presented herewith, it must be clearly understood not only that various accessory minerals are not listed, but also that adjacent types in the classification are not always sharply defined because many intermediate (gradational) types are known.

*Comments on the Classification.* The classification involves two important factors—texture and mineral content. Reading horizontally all rocks in a row have a similar texture, and reading vertically all rocks in a column have a similar mineral content. This very brief classification gives a fair idea of some of the more common kinds of igneous rocks and their relationships, but a complete classification would involve many other names and it would be much more complicated.

The chief minerals in the granitoid rocks named in the table are generally large enough to be recognized by the naked eye or with the help of a magnifying glass.

In the porphyritic rocks the relatively large minerals can usually be determined by the unaided eye or with a lens. The other minerals of the porphyries may or may not be recognizable in the same way, depending upon the size of the minerals and the degree of crystallization of the rock. Thus a rhyolite porphyry may be in part uncrystallized or glassy, and hence show no minerals or the minerals may be very fine grained.

Rocks with a felsitic texture are generally so fine grained, or even

*Principal Kinds of Igneous Rocks*

| | | *Orthoclase and quartz, etc.* | *Orthoclase, but no quartz, etc.* | *Plagioclase and biotite or hornblende, etc.* | *Plagioclase and pyroxene, etc.* | *No feldspar. Biotite, hornblende, or pyroxene, etc.* |
|---|---|---|---|---|---|---|
| Mainly Volcanic | *Glassy or Fragmental.* | Rhyolite obsidian, tuff, breccia, etc. | Trachyte obsidian, tuff, breccia, etc. | Andesite obsidian, tuff, breccia, etc. | Basalt obsidian, tuff, breccia, etc. | Limburgite tuff, breccia, etc. |
| | *Felsitic.* | Rhyolite. | Trachyte. | Andesite. | Basalt. | Limburgite. |
| Intermediate | *Porphyritic.* | Rhyo. and Gra. porphyries. | Trach. and Sy. porphyries. | And. and Dior. porphyries. | Bas. and Gab. porphyries. | Lim. and Per. porphyries. |
| Mainly Plutonic | *Granitoid.* | Granite. | Syenite. | Diorite. | Gabbro. | Peridotite. |
| | | Granite family. | Syenite family. | Diorite family. | Gabbro family. | Peridotite family. |
| | | Usually light-colored | | Usually dark to black. | | |

partly glassy, that the minerals can seldom be identified without the aid of a microscope.

Glassy rocks of course show no minerals, but, under the microscope, suggestions of some incipient crystals may appear. The place of a glassy rock (obsidian) in the table can be told only by a chemical analysis which indicates about what the minerals would be if the magma had crystallized.

Fragmental rocks can be classified as to mineral content only when enough minerals of the fragments can be made out.

Having a knowledge of the common textures and minerals involved in the above table, the student should carefully examine specimens of most of the types of igneous rocks listed.

## Metamorphic Rocks

**Meaning of Metamorphism.** *Metamorphism* means any change in mineral composition, structure, or texture of an igneous or a sedimentary rock whereby the original rock character is notably altered.

In many cases the products of metamorphic action look utterly different from the rocks from which they were derived, while in many other cases some of the original features are retained. Simple consolidation of loose sediment, like that of clay into shale, is not regarded as a metamorphic process. Disintegration and decay of rocks under the action of the weather (atmospheric agencies) are, however, processes of metamorphism in the broad sense of the term.

Sedimentary rocks which have been thoroughly metamorphosed "are much harder, denser, more crystalline, and the fossils, and perhaps even the marks of stratification, have been more or less completely obliterated. As to the igneous rocks, the particular features which distinguish them may disappear, and they may assume a banded appearance and cleavage which resemble those of sedimentary kinds" (Pirsson). Without careful field study, it is sometimes impossible to tell whether a given metamorphic rock was originally igneous or sedimentary.

**Agencies of Metamorphism.** How do igneous and sedimentary rocks become metamorphosed? Brief mention will now be made of the principal agencies of metamorphism. *Liquids*, particularly water on and in the earth, are often effective agents of alteration of rock material by dissolving it, after which it may crystallize in new mineral combinations.

Various *gases* and *vapors*, especially those which escape from molten masses into surrounding rocks, often effect important chemical changes and rearrangements of mineral matter in rocks.

*Heat* is an important metamorphic agency. By it liquids and gases are rendered much more active. It helps to alter the composition of many minerals, and to bring into existence new ones. A sedimentary rock mass may be metamorphosed by heat along the border of a molten mass which is intrusive into the sediment. A rock mass may be heated not only by a hot, igneous body, but also by deep burial within the generally heated crust of the earth. Some heat may also result from disturbances of the crust due to shrinkage of the earth.

*Lateral pressure* is a very important agency of metamorphism of both igneous and sedimentary rocks. We shall learn in another chapter that the crust of the earth is, and has been, in many places subjected to tremendous stresses and compressive forces due to earth shrinkage, causing rocks to be bent, mashed, sheared, fractured, and often locally crumpled into mountain ranges. Mineral grains or rock fragments may thus be crushed or flattened; mineral rearrangement may take place; and the rock structure and texture may be greatly changed.

FIG. 37. Slaty cleavage structure developed across bedding of sharply folded strata. Near Walland, Tennessee. (After Keith, U. S. Geological Survey.)

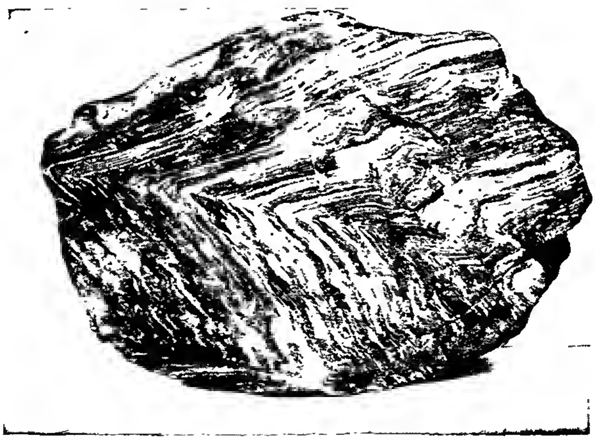


FIG. 38. A specimen of crumpled schist. One-fourth natural size.

*Downward pressure* exerted upon deeply buried rocks, particularly sediments, aided by the heat of the earth's interior, and often by water or other liquid, is probably another important factor in the transformation of rocks.

In some cases the agencies mentioned may operate only very locally, causing *local metamorphism*, while in other cases they may bring about great changes over extensive areas, causing *regional metamorphism.*

**Minerals and Structures of Metamorphic Rocks.** Relatively few common minerals make up the great bulk of metamorphic rocks. Chief among them are quartz, the feldspars, the micas, the amphiboles, the pyroxenes, calcite, and dolomite. Most igneous and metamorphic rocks are similar in regard to their distinctly crystalline appearance, but they are unlike in that the metamorphic rocks usually have a parallel structure or arrangement of mineral grains, often resembling stratification. In some cases this structure is parallel to original bedding of strata, but more often it is not. It should be kept in mind that not all igneous and metamorphic rocks are crystalline, and that not all metamorphic rocks possess a parallel structure. Such cases are, however, relatively exceptional.

FIG. 39. A specimen of granite gneiss. Two-thirds natural size.

*Foliation* is the arrangement of the mineral constituents of a metamorphic rock with their long axes more or less parallel, thus causing the rock to have a parallel structure. It is a secondary structure, that is, it is developed in the original rock mainly by pressure after the rock was formed as such. A rock possessing foliation is called a *foliate.* Well-developed foliation causes *cleavage*, that is, a tendency for the rock to split in layers parallel to the foliation. Well-developed foliation in a very fine grained, not obviously crystalline, rock is called *slaty cleavage*, well illustrated by common roofing slate. A highly crystal-

line rock with an excellent foliation (or cleavage) is called a *schist* (Fig. 38). A crystalline rock with crude foliation is called a *gneiss* (Fig. 39). The term *gneissoid* may be applied to an igneous rock in which a crude foliated structure is developed during the consolidation of the magma.

**Kinds of Metamorphic Rocks.** Igneous rocks which have their foliation impressed upon them after complete solidification of the magma may be named *granite gneiss* or *schist*, etc., according to the kind of igneous rock involved. Those whose foliation develops during the process of solidification of the magma may be named *gneissoid granite*, *gneissoid diorite*, etc., according to the kind of rock. Some *hornblende schist* (or *amphibolite*) is merely foliated hornblende-rich igneous rock. Some slate is igneous rock with a typical slaty cleavage. Among the non-foliated, igneous, metamorphic rocks, *serpentine* and *soapstone* are chemically much altered gabbro, peridotite, etc., and some lavas have also been notably altered chemically.

Many names have been applied to various foliated sedimentary rocks. Thus *mica* or *hornblende schist* and *gneiss* are thoroughly crystalline foliates rich in the particular minerals mentioned. Both of these minerals may occur in the same rock, usually also with feldspar. They are mainly foliated shales. *Quartz schist* is foliated, impure sandstone often containing mica. *Conglomerate gneiss* is simply foliated conglomerate, and *marble gneiss* is simply foliated impure limestone. Most *slate* is foliated shale with highly developed slaty cleavage but with very little crystallization. Among the non-foliated metamorphosed sedimentary rocks are *quartzite*, a usually massive rock derived from rather pure sandstone; *marble*, derived from limestone; *anthracite*, which is altered bituminous coal; and certain metamorphic rocks produced by the heat of magma near its contact with sedimentary rocks.

# CHAPTER V

## ROCK WEATHERING

### General Significance of Weathering

All the materials of the outer or crustal portion of the earth are subject to ceaseless change. Under the action of the weather and other more or less closely related agencies, even the hardest and most resistant rocks crumble or decay in the course of time (Figs. 40, 43, 45, and 46). Weathering effects are, as a rule, scarcely noticeable during the ordinary span of a human life, but, during the eons of geological time, weathering processes have been relentlessly at work upon the surface and near-surface portions of the earth, causing such tremendous quantities of rock material to be broken up and decomposed that the lands have been profoundly affected. In fact, most of the materials by far which make up the vast bodies of sedimentary rocks are products of rock weathering which have been transported from their places of origin.

In its earlier application, the term weathering usually included only the direct action of the weather or atmospheric agencies upon rocks and minerals, causing them to break up or decay. According to present usage, *weathering* comprises all processes, such as mechanical action of temperature changes, freezing of water, organisms, rain water, and lightning, and the chemical action of atmospheric gases, water, and organisms, whereby rocks at and near the earth's surface break up, decay, or crumble. Even as thus broadly defined, the direct action of the weather is the most important factor in the complex set of processes called weathering.

### Rate of Weathering

The rate of weathering depends upon the nature of the rocks, and the kinds and conditions of the weathering agents which operate upon them. It is a matter of common knowledge that many stone buildings and monuments show marked effects of weathering. An excellent case in point is Westminster Abbey in London which was built of weak, rather porous stone in the thirteenth century. Many of its outer stones

are badly weathered, some of its ornamental, carved parts having been reduced to shapeless forms. Many of the exterior carvings of soft limestone of the Louvre in Paris are also badly weathered. Inscriptions on many tombstones and monuments only one or two centuries old are often nearly, or quite, illegible, due to weathering. Weathering is, however, much less rapid in the case of hard, resistant rocks. Thus, even the polished surface of a very resistant rock, like granite or quartzite, may be preserved for many years although exposed to very vigorous and changeable weather conditions. There are ways of estimating that many of thousands of years are required for enough weathering to develop a soil a few feet thick from (and resting upon) a hard rock like granite.

## Complexity of Weathering Processes

Broadly considered, there are two general processes of weathering—one mechanical, and the other chemical. In *mechanical weathering* the rock breaks up or crumbles with little or no change in the composition of the material. It is essentially a physical process of disintegration. In *chemical weathering* the composition of the rock or mineral matter is more or less altered during its breaking up. It is essentially a process of decay or decomposition. "Although the process of disintegration and decomposition may be thus distinguished, nevertheless the two processes very commonly operate together in nature, now one and now the other being predominant.

As stated by Blackwelder: "Rock weathering is due to the interplay of a number of processes. . . . Some of them are purely chemical, and others are strictly mechanical. . . . Doubtless some of these processes are everywhere of minor importance, while others may be powerful only at certain times or locally. . . . It is more than probable that one of these processes may facilitate a second, and that in turn a third. By such coöperation several agents of weathering may induce rock fracture where no one of them could do it alone."

## Mechanical Weathering

**Freezing and Thawing of Water.** Not only in cold countries, but also in the mountains of regions with generally mild climates, alternate freezing and thawing of water is an effective agency in breaking up rocks, especially where soils are absent or very thin. Most relatively hard rocks contain not only numerous natural fractures called joints

which separate them into more or less distinct blocks, but also small crevices, fissures, and pores. Surface water may fill such openings. Such water expands about one-tenth of its volume on freezing, and exerts the tremendous pressure of many thousands of pounds per square inch upon the walls of the opening or fissure. If the rock is favorably situated, the pressure will widen the opening a little. Repeated freezing and thawing of water which finds its way into such openings finally causes even the hardest rocks to be mechanically broken up into smaller and

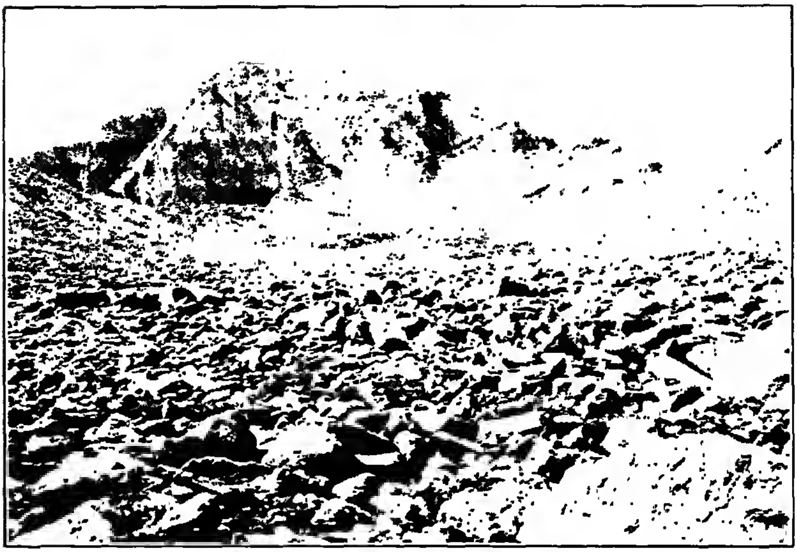


FIG. 40. A field of large angular blocks derived from granite bedrock mainly by freezing and thawing of water ("frost action") in joint cracks. North side of Long's Peak, Colorado, at an altitude of 12,000 feet.

smaller fragments. Jointed rocks situated on the faces of cliffs and steep slopes are especially subject to such action, as are also jointed or fissured boulders, pebbles, and even soil particles.

**Insolation.** By *insolation* is meant changes of temperature, involving mostly variations in supply of heat from the sun, causing expansion and contraction of rocks and minerals as factors of mechanical weathering. The principle involved is that all parts of a rock mass do not expand and contract at equal rates when subjected to temperature changes, and so stresses are set up which cause the rock to break. Such effects are most conspicuous on high mountains, and on deserts not only

because rocks are there generally barren, but also because a daily range of 50 to over 100 degrees in temperature is frequent. In many deserts the outer portions of rock ledges and boulders exposed to the rays of the sun are heated to temperatures of 100° to 150° during the day and, therefore, expand, but during the night the temperature commonly falls 50° to 100°, and the outer portions of the same rocks contract notably. Cool rain of a sudden storm falling upon hot rocks also cause a quick lowering of temperature of their outer portions. Such rapid changes, causing repeated strains of this kind between the outer and inner portions of the rocks, finally cause the latter to break just as cold glass breaks when plunged into hot water. Most rocks consist of two or more kinds of minerals, each of which expands at a different rate, and so additional, minor stresses and strains are set up, tending to pull apart the minerals and disrupt the rocks.

Blackwelder has recently questioned the importance of insolation as a factor of weathering. It is doubtful, he says, if "insolation is ever the sole unaided cause of rock fracture. However, it seems at least possible that, by setting up strains in rocks, it aids in loosening the cohesion of minerals, facilitates the entrance of moisture, and thus promotes the breakage of the rock by expansion due to chemical changes." He believes that the principle is much the same as that involved in spheroidal weathering discussed beyond in this chapter.

As the mineral grains of a rock become loosened by temperature changes, water can more readily enter the body of the rock so that, in sufficiently cold climates, freezing of the water will aid in disrupting the rock.

**Exfoliation.** When, due to various causes, usually including temperature changes, the outer portions of rocks peel, or scale, off in small or large slabs or sheets, the process is called *exfoliation*. It seems to be especially effective in uniform, massive rocks, with fairly large mineral grains, such as granite or diorite. Rock surfaces tend to round off by this process, excellent examples being Stone Mountain in Georgia, and many of the high mountains of the central and southern Sierra Nevada Range in California (Fig. 41). The principle of exfoliation is often like that which causes so-called "spalling" of stones in buildings during fires, particularly when cold water is thrown on the hot surfaces. Spalling was wonderfully illustrated in the ruins of the famous Rheims Cathedral.

There is reason to believe that, in many cases, large and small sheets of granite and other massive rocks shell off as a result of relief of

pressure due to removal of much overlying material by erosion (Fig. 67). It is explained beyond in the discussion of joints. This process may be an important cause of exfoliation.

**Mechanical Action of Organisms.** Both directly and indirectly, plants and animals accomplish considerable work of rock disintegration. Roots and trunks of plants, especially of the higher forms, like trees, insert themselves in rock crevices and cracks, and as they grow they exert a powerful force, often sufficient to wedge the rock apart (Fig. 42). Repetitions of this wedgework process often cause the rock to be broken into small fragments. Various rootless plants, such

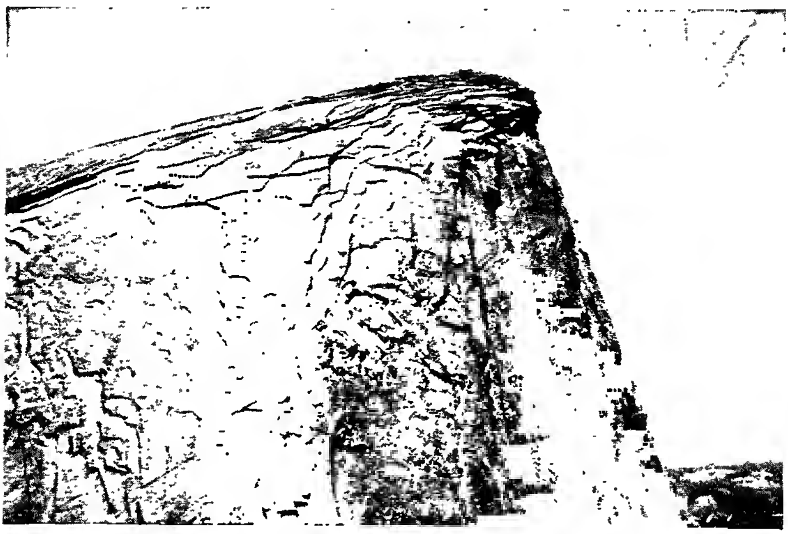


Fig. 41. Exfoliation of granite on a large scale. Half Dome, Yosemite National Park.

as lichens, attach themselves to rock surfaces and loosen off rock particles as they grow.

Indirect actions are the overturning of trees, causing relatively fresh rock materials to be brought to the surface and better exposed to weathering agents, and the successive growths of roots, causing the soil to be made more open and accessible to weathering agents.

Burrowing animals, such as earthworms, ants, gophers, ground squirrels, and woodchucks, aid the action of weathering agents both by bringing fresher materials to the surface and by allowing more ready access of such agents to the surface materials. Earthworms perform a remarkable work of soil disintegration. They pass soil through their bodies

in order to extract the vegetable matter from it, and in this way the bits of soil are ground up into still finer particles. It has been estimated that, in humid, temperate regions, the many thousands of earthworms per acre completely work over a soil layer from six inches to a foot thick once every half-century.

**Action of Rain, Wind, and Lightning.** Mechanical weathering is accomplished in some measure on relatively loose rocks and soils by the impact of raindrops and by the force of the wind, whereby rock

FIG. 42. A growing tree splitting a boulder of granite. Custer County, South Dakota. (Courtesy of the U. S. Forest Service.)

fragments are loosened from their positions. Lightning often shatters rocks in regions where electrical storms are frequent, but its total effect is relatively small. Forest fires caused by lightning subject rocks to intense heat locally and destroy vegetation, thus aiding weathering.

## CHEMICAL WEATHERING

**Solution.** Most rocks are only very slightly and slowly affected by the solvent action of perfectly pure water. Such water is, however, not found in nature because certain gases, particularly oxygen and car-

bonic acid gas, are always dissolved in it, causing the solvent power of the water to be notably increased. Pure limestone is slowly, but completely, soluble in such water, and the dissolved matter is carried away by streams. In an impure limestone, only the impurities tend to remain. When rocks, whose mineral grains are cemented, or held together, by limy material, are subjected to the action of carbonated water, the limy material is dissolved and carried away, and the sand grains are left. Thus the rock crumbles. Many waters have their solvent power increased by the presence of other acids obtained from

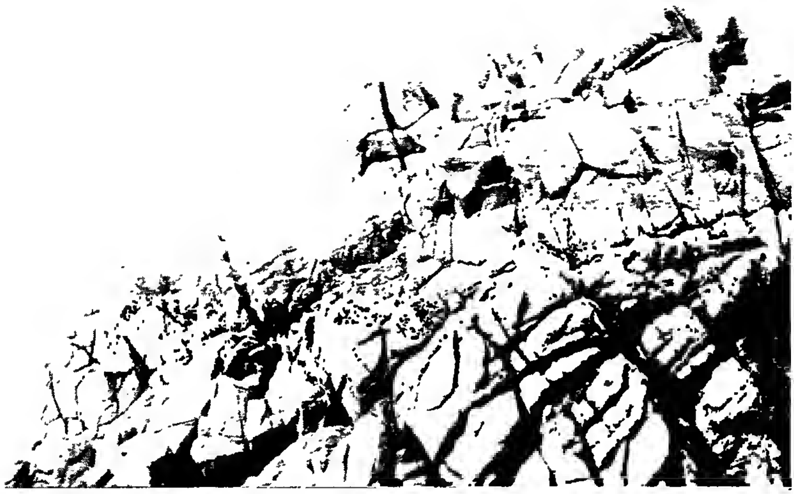


FIG. 43. A ledge of granite showing how joints, being enlarged by atmospheric agents, facilitate both mechanical and chemical weathering of the rock. Near Lone Pine, California.

decomposing organic matter, volcanic gases, etc. Natural waters thus charged with oxygen, carbonic acid gas, and other acids attack and dissolve minerals with greatly varying degrees of effectiveness. If even only one kind of mineral in a rock is but slightly dissolved, the adhesion of the mineral grains is lessened, and the rock tends to crumble. Some minerals are exceedingly resistant to solution. Thus quartz is only slowly soluble even in hot alkaline water. Such common minerals as gypsum and calcite are more or less readily soluble in hot, carbonated water. Salt is of course easily soluble in cold water

**Carbonation, Oxidation, and Hydration.** Carbonic acid gas, which occurs in air, water, and soil, has the power of chemically uniting with,

and altering the composition of, certain minerals of rocks. Thus many rocks contain the chemical elements calcium and iron with which carbonic acid gas may combine to form carbonates of calcium and iron. Such a process is called *carbonation.* The resulting carbonates are readily taken into solution and carried away by water, thus causing the rocks to crumble. A slow, but very important and widespread, process of this kind is the alteration of the very common mineral feldspar by carbonated water to kaolin (or clay), silica (or quartz), and a soluble carbonate. This action takes place during the decomposition of a hard, resistant igneous rock, like granite.

Oxygen occurs in air and soil, and dissolved in water. It is a very important chemical agent of decay of many rocks and minerals. The process of *oxidation* consists in the chemical union of oxygen with any chemical element, as very often happens with the iron contained in such common minerals as pyrite, biotite-mica, hornblende (an amphibole), and augite (a pyroxene). The familiar rusting of iron involves oxidation, that is, a chemical union of the iron with oxygen of air or water.

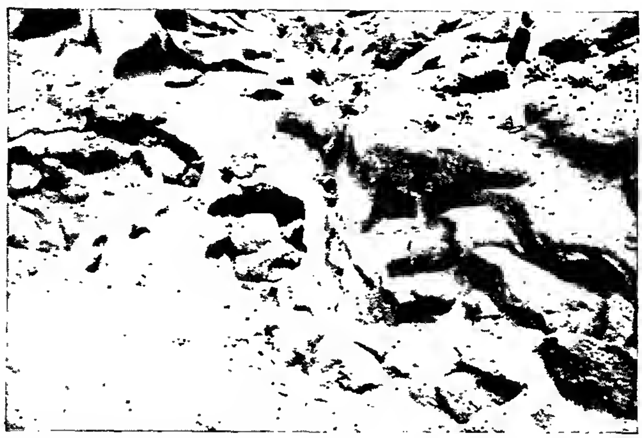


FIG. 44. A ledge of rock showing a cavernous appearance due to removal of certain more soluble and easily weathered material. North of Daggett, California.

The process of *hydration* consists in the chemical union of water with certain compounds. The principle is well illustrated by the rusting of iron which, on exposure to air and moisture, first unites with oxygen to form iron-oxide, and then unites with water to become yellow or brown hydrated iron-oxide (the so-called "rust"). Many rocks con-

tain iron not as such, but in chemical combination with other elements. When such iron-bearing minerals in rocks are subjected to the action of oxygen and water, the iron very commonly unites with both oxygen and water to form various hydrated iron-oxides, ranging in color from yellow to reddish brown. Many of the striking colors of great rock formations of the earth have thus been produced. An excellent, large-scale example of gorgeous coloring so produced is the Grand Canyon of Yellowstone Park whose iron-rich lava rock has been highly decomposed.

Carbonation, oxidation, and hydration are all very important factors in the chemical weathering, or decomposition, of rocks. Increase in volume of the rocks affected is caused by all three processes, and the stresses and strains which develop as a result of volume increase tend to cause the rocks to crumble. In some cases the resulting materials, such as carbonates, are dissolved and carried away by water, thus increasing the porosity, and lessening the strength of the rocks affected.

**Chemical Action of Organisms.** Bacteria are very abundant not only in soils, but also on bare rocks. One group has the remarkable power of forming nitric acid from certain constituents (especially ammonia) of air, water, and soil, and this acid attacks and alters various minerals. Decaying plants, as well as roots of living plants, produce carbonic acid and other acids which alter the composition of various minerals in rocks.

Certain animals also bring about chemical weathering. Thus the soil particles which are worked over and carried by ants and earthworms are acted upon by organic chemical agents or acids secreted by these animals.

**Spheroidal Weathering.** When water containing dissolved gases enters a rock mass (particularly one which is fine grained and homogeneous), which is divided into rectangular blocks by fissures, such as joint cracks (Fig. 45), the solutions work their way along the cracks and attack all surfaces of the rock with which they come into contact, and there cause decomposition which slowly eats into the blocks of solid rock. Not only do the edges, and still more so the corners, have greater surfaces exposed to the solutions, but also they are attacked from two or three directions at once with likelihood of being affected by the strongest solutions. The corners of the blocks of rock will, therefore, most rapidly be weathered, the edges next most rapidly, and the faces least. The new substances thus formed by oxidation, hydration, and carbonation are greater in volume than the unaltered material, and so "strains are set up which tend to separate the bulkier new material from the

core of unaltered rock. . . . The squared block is by this process transformed into a spheroidal core of still unaltered rock wrapped in layers of decomposed material, like the outer wrappings of an onion" (Hobbs). They are usually embedded in thoroughly decomposed material. The

FIG. 45. Spheroidal weathering in basalt. Western Santa Monica Mountains, California (Photo by U. S. Grant, IV.)

process described is called *spheroidal* or *concentric weathering*, and the resulting boulders are called *boulders of decomposition.* It is to be noted that they are produced mainly by chemical weathering, whereas boulders of exfoliation result from mechanical weathering.

## Accumulations of Products of Weathering

**Talus.** A mass of rock fragments of various sizes and shapes resulting from the weathering of a cliff or steep slope, and lying at the base of the cliff or slope is called *talus*. Temperature changes (exfoliation), and freezing and thawing of water in cracks, are the principal weathering agents which produce talus material. As the fragments are loosened from the cliff or steep ledge they fall, slide, or roll down until the angle of slope is too low for them to continue. The angle of slope of a talus pile generally ranges from about 25° to 40°. The tendency is for the largest blocks of rock to accumulate toward the bottom of a talus slope because the momentum carries such masses farther. In

mountainous regions of severe climate with great and rapid changes in temperature, the conditions are especially favorable for large accumulations of talus, such deposits attaining lengths and depths of hundreds, or even thousands, of feet (Fig. 46).

**Boulder Fields Due to Weathering.** Fields of rounded boulders may also result primarily from chemical weathering. Thus, the body of bedrock may be attacked much more vigorously by agents of decomposition along cracks, fissures, or more porous parts than it is in its more solid portions between the cracks or porous parts. There also

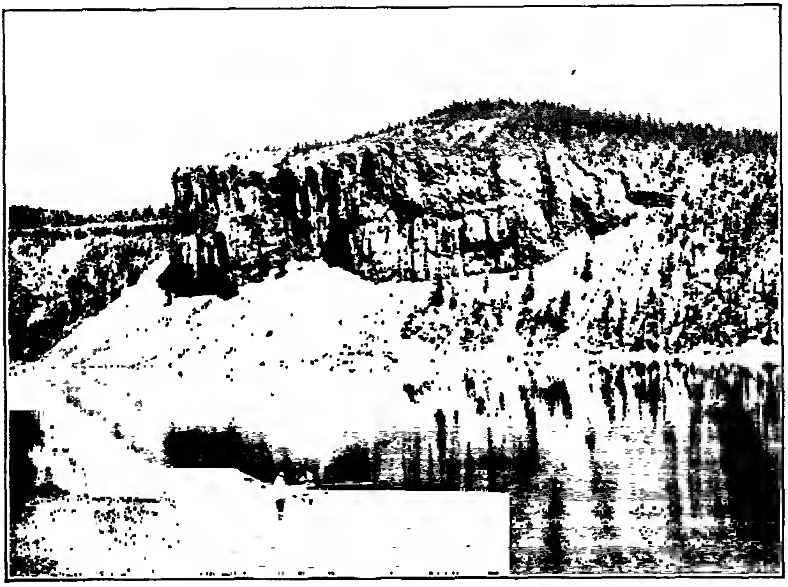


FIG. 46. A cliff of jointed lava and talus slope. Crater Lake, Oregon. (Photo by J. S. Diller, U. S. Geological Survey.)

may be local portions of the bedrock which are harder or more resistant to the weathering agents than the general body of the rock. In either case, the tendency is for more or less rounded blocks of relatively fresh rock to be left as cores in the midst of highly decomposed material. Removal of the decomposed material by rain, streams, or wind will tend to leave an accumulation of the boulders at the surface. Some of the boulders in this category are boulders of decomposition already described as resulting from spheroidal weathering.

**Mantle Rock.** Most of the lands of the earth are covered by a superficial layer of loose, earthly material called *mantle rock* which,

wherever it occurs, rests upon the bedrock of the earth's crust. Where the bedrock is exposed at the earth's surface it is said to *outcrop*. There are two important kinds of mantle rock. One is the mantle rock which now rests upon the bedrock just where it was formed through the processes of weathering, that is, it is *residual mantle rock*, representing a direct accumulation of weathered rock material. The other is mantle rock which has been carried to its present position upon the bedrock, mainly by water, wind, or glaciers, that is, it is *transported mantle rock*, representing an indirect accumulation of material mostly made up of

FIG. 47. A highly jointed mass of diorite almost completely covered by boulders of weathering. Some of the jointed bedrock shows at the right. Seven miles west of Coyote Well, California.

products of weathering. Our present concern is chiefly with the residual rock mantle, while transported mantle rock is treated in several of the succeeding chapters. The residual mantle does not rest by sharp contact upon the bedrock, but rather it grades downward through partly weathered rock into unweathered rock. The transported mantle rock rests characteristically by sharp contact upon the bedrock from which latter it usually differs notably in composition. Although the processes of weathering are universal and unceasing in their action over all the lands, nevertheless there are many places where conditions favor removal of the products of weathering fully as fast as they are formed, and so bare rock surfaces are left exposed.

FIG. 48. Fresh granite (at bottom) grading upward through rotten rock and subsoil into true soil. Washington, D. C. (After G. P. Merrill, U. S. National Museum.)

The very widespread mantle rock is of great geological importance in several ways. Most of the vegetation of the land for countless ages has grown in its upper portion. It is the chief source of supply of the sediment carried by streams, and thus a great aid to erosion as we shall learn in a succeeding chapter. As an actual mantle it greatly retards the rapidity of weathering of the bedrock underneath it.

**Soils.** The soils of the world are either directly or indirectly very largely the products of rock-weathering. To a very minor extent

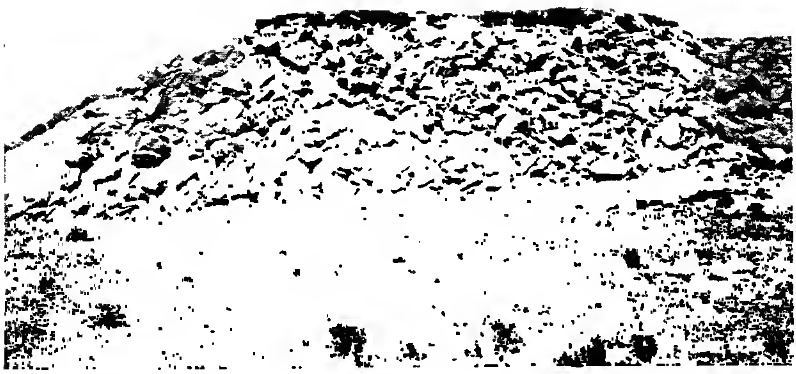


FIG. 49. A hill of soft shale capped with a bed of hard sandstone. The shale slopes are strewn with angular blocks of sandstone derived from the well jointed cap rock. Petrified Forest, Arizona.

soils result from vegetation. In the strict sense of the word, *soil* is the relatively porous, fine grained, upper portion of the mantle rock containing an admixture of vegetable matter, and capable of supporting plant life. The term is, however, often used rather loosely. Just as we distinguish two general kinds of mantle rocks, so we must recognize two kinds of soils, namely, residual and transported. Residual soils here claim our chief attention because they are direct accumulations of products of weathering.

*Residual soil,* with its admixture of decomposing vegetable matter causing it to have a more or less dark color, always grades downward

into *subsoil* which usually contains fragments of partly decayed rock and little or no vegetable matter. The subsoil in turn passes by imperceptible change downward into partly decayed *rotten rock*, and this latter finally grades into the underlying, unaltered, *fresh rock*. These various stages are well illustrated by Figure 48.

Residual soils are very extensively developed in the southern states of the United States, and *transported soils*, left by the great glacier of the Ice Age, are very widespread over the northeastern states. True soils are usually not more than a few feet thick, but soil plus subsoil and rotten rock may be scores, or exceptionally hundreds, of feet thick.

Considering the large number of different minerals and rocks which give rise to soils, and the varying conditions under which the materials are weathered, it is not surprising that there are many kinds of soils. In fact, probably no two soils from reasonably separate regions are just alike. Only a few of the more general soil types will be mentioned briefly. Thus, *clay* consists very largely of exceedingly finely divided kaolin. *Sand* is composed of sand grains, mostly quartz. *Loam* is a mixture of sand and clay. *Muck* is a very dark soil exceedingly rich in decayed vegetable matter. *Marl* is a soil rich in limy material, that is, in carbonate of lime. These very common kinds of soils show all sorts of gradations into each other.

## Movements of Weathered Products

We shall now briefly consider some of the ways by which products of weathering are moved from their places of origin.

Attention has already been called to the accumulation of talus by the falling, rolling, and sliding of rock fragments which are loosened by weathering from cliffs and steep slopes. Closely related to this action is the movement of rock débris in so-called *rock glaciers* or "stone rivers" under certain conditions of cold climate. These are great masses of talus hundreds or even thousands of feet long, which slowly move down mountainsides or steep valleys, as in parts of Colorado. Externally they give somewhat of the appearance of a glacier. The motion results from gravity aided by alternate freezing and thawing of water which fills the spaces between the rock fragments.

*Soil creep* is a common process by which mantle rock and soil move down slopes. When water-charged soil freezes, the rock fragments are

lifted somewhat by the expansion at right angles to the slope or surface of the hill or mountain. On thawing, the rock fragments are pulled down vertically by gravity, and thus they move downhill a little. Repetition of this process causes the whole soil mantle to slowly move or "creep" down the slope.

Sudden movements of masses of rock débris down mountainsides or

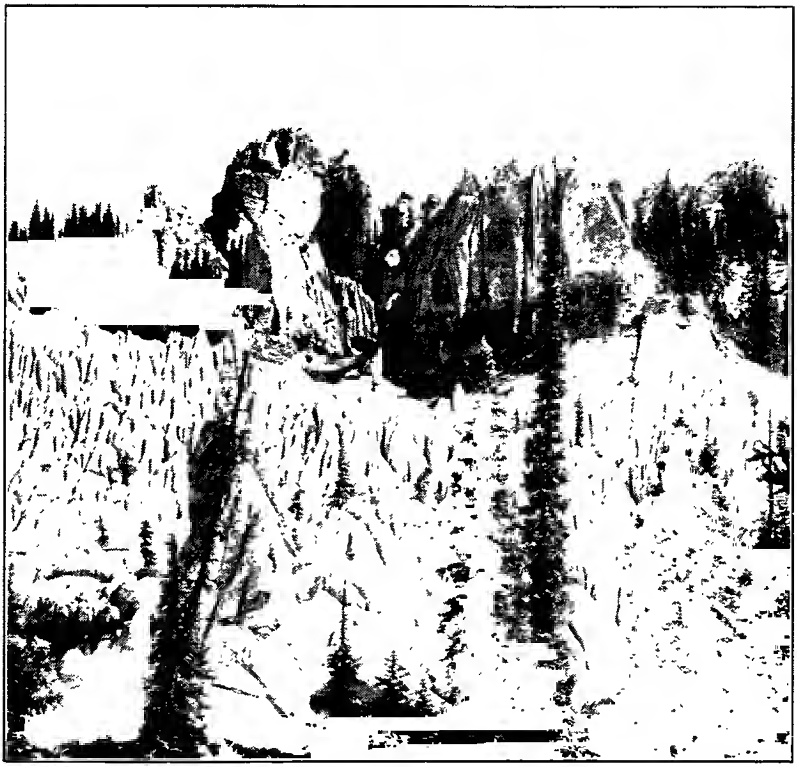


FIG. 50. Volcanic tuff weathered and intricately sculptured, mainly by rain wash. Wheeler National Monument, Colorado. (Courtesy of the U. S. Forest Service.)

hillsides are called *landslides*. Among various causes of such movements are earthquake shocks; undercutting of the masses of débris by streams, thus weakening the support toward the bottom; and saturation of the mass with water, thus increasing its weight and lessening the friction of the rock fragments. In many cases not only the soil or mantle rock, but also much bedrock of a mountainside, takes part in a

landslide. This happened at Frank in Alberta, Canada, in 1903, when the whole face of a mountain several thousand feet high suddenly gave way, causing about 40,000,000 cubic yards of rock material to rush down into, and partly across, a valley. Landslides are common, and many disastrous ones have occurred. Avalanches of snow also often carry much rock débris down with them.

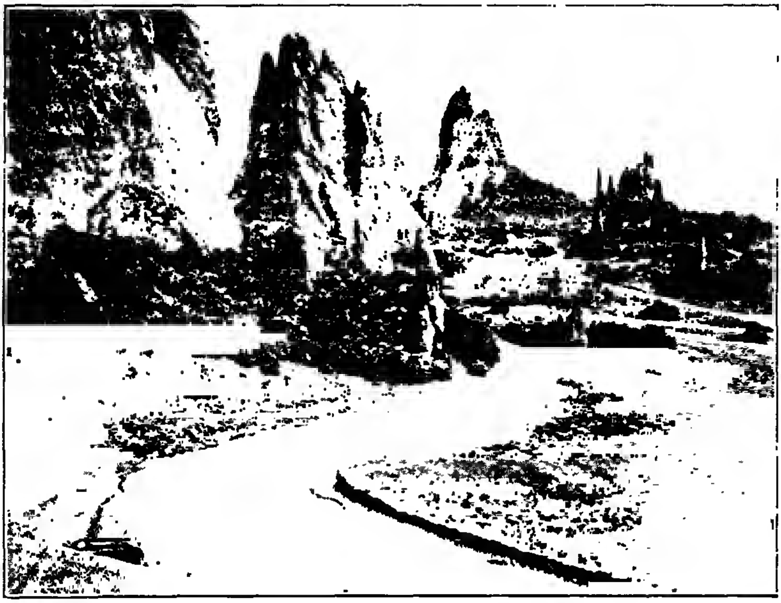


FIG. 51. Effects of unequal weathering and erosion of nearly vertical beds of red sandstone. Garden of the Gods, Colorado.

By the direct action of rain wash, loose materials not too thoroughly protected by vegetation are carried from higher to lower levels.

Streams, wind, and glaciers are by far the greatest agents of transportation of mantle rock, including soil. Water is most effective in humid regions; wind in arid regions; and glaciers in cold regions. All of these are very important geologically, and they are dealt with at some length in succeeding chapters.

## Sculpturing Effects of Weathering

**Effects of Differential Weathering.** Most rock masses are not uniform in composition, texture, and structure. Some portions are, therefore, more readily attacked by agents of weathering than others, so that they are eaten into or etched out, while the more resistant parts are left to stand out in relief. All such cases of unequal weathering of rock masses are referred to as *differential weathering*. Such unequal weathering is a very common phenomenon to be observed in exposed bedrock almost anywhere. A few examples will suffice to make the principle clear.

Fig. 52. A remarkably balanced rock resulting from unequal weathering. Near La Veta, Colorado. (Courtesy of the U. S. Forest Service.)

Limestone or limy sandstone is particularly likely to become honeycombed, deeply pitted, or fluted where agents of weathering etch out the weaker and more soluble portions.

Where a rock mass of any kind is transected by natural cracks called *joints* (see Fig. 65), the tendency is for the cracks to become enlarged while the intervening masses of rock stand out more and more separately in relief. Where vertical joints cross-cut each other in closely spaced groups, leaving relatively large non-jointed blocks of rock between them, the tendency often is for the weather to remove the jointed material and leave the solid cores which themselves become less angular under the action of the weather. Among many excellent examples are the Cathedral Spires in the Garden of the Gods, Colorado (Fig. 51), and the

many wonderful natural monuments near Douglas, Arizona (Fig. 53). Great joint blocks only partly etched out are wonderfully displayed in the walls of Zion Canyon, Utah (Fig. 65). A most remarkable maze of joint columns occurs in Bryce Canyon, and also in Cedar Breaks, Utah.

Fig. 53. Joint columns resulting from weathering of rhyolite lava. Near Douglas, Arizona. (Photo by J. J. Armstrong.)

Where veins (p. 241) or dikes (p. 97) of hard materials intersect ledges of weaker rocks, the vein or dike material often stands out in bold relief in the midst of the etched out general body of weaker rock (Fig. 82).

Rock formations which are arranged in layers (usually stratified) often possess variable degrees of resistance to the weather. Where such rocks are in horizontal position or gently inclined, the tendency is for the more resistant layers to form cliffs, or even overhanging ledges, while the weaker layers crumble down to talus slopes. Such differential weathering is grandly displayed in the Grand Canyon of Arizona (Fig. 112). If the rock layers are steeply inclined or vertical, the tendency is for the more resistant layers to stand out in relief (Fig. 51).

It is evident, from what has been said, that differential weathering plays an important part in the detailed sculpturing of the land. Many of the more striking, minor features of landscapes, such as jagged peaks, pinnacles, ridges, and cliffs, have been so sculptured. Acting alone,

however, differential weathering cannot proceed very far because the weathered products must be removed (eroded) by some agent such as wind or running water in order that new surfaces of the rock may be exposed to the sculpturing processes.

## Relation of Weathering to Erosion

The term *erosion* comprises all the processes whereby the lands are worn down. More specifically, it involves the breaking up, decay, and transportation of materials at and near the earth's surface by weathering and solution, and by the mechanical action of running water, waves, moving ice, or winds which use rock fragments as tools. The term "erosion" is one of the most important in the science of geology. It includes five processes as follows: weathering, corrasion, solution, pressure, and transportation. *Weathering,* as just explained at some length, causes much rock material to be broken up and decomposed. It is, therefore, an important preparatory process, or factor of, erosion.

## CHAPTER VI

# STRUCTURE OF THE EARTH'S CRUST

### Structure Section

It is usually an important part of the business of the geologist, in reporting on the geology of a region, not only to make a map depicting the surface distribution of the various rock formations, but also to

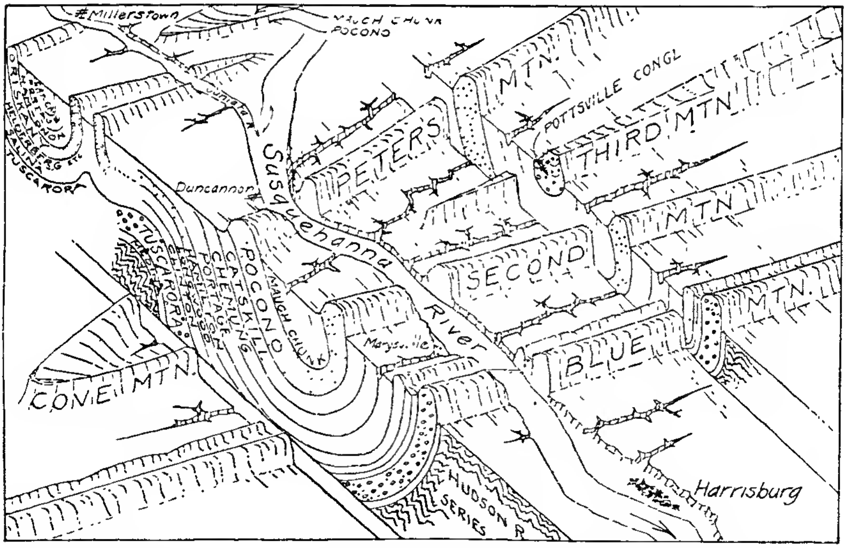



Fig. 54. Diagram illustrating structure sections through the folded, mountainous region west of Harrisburg, Pennsylvania. (Drawn by A. K. Lobeck.)

represent graphically the underground relations of the various formations by means of so-called "structure sections."

A *structure section* shows the relations of the rocks of a region as they would appear, from the surface downward, on the face of a

vertical slice through a part of the earth's crust along a certain line. Thus, in Figure 54 the structure section shows the subsurface positions of the various formations along the line AA of the accompanying areal geologic map. In a block diagram (Fig. 201) it is feasible to combine with structure sections on two sides, either the surface distribution of formations, or the relief, or both. A careful study of Figures 54 and 201 should serve to make clear the principle of the structure section.

## Outcrop, Dip, and Strike

**Outcrop.** Several terms are very commonly employed in dealing with the arrangement (*structure*) of the rocks of the earth's crust. One of these terms is *outcrop*, which means any surface exposure of the underlying bedrock. The term *rock exposure* is sometimes used as a synonym. It so happens that the bedrock formations are, in most regions, largely concealed under cover of soils, loose rock fragments, glacial deposits, vegetation, water, ice, or snow. In high mountains, or in other regions where erosion is proceeding rapidly, outcrops are generally much more numerous and extensive than in regions where sediments have recently been, or are being, deposited. It is very generally true that the surface distribution of rock formations, and the underground structures of a region, are worked out by a careful study of the outcrops. Where the geologic structure is simple, relatively few outcrops may suffice, but where it is very complex many outcrops must be found and carefully studied in order to determine the structure.

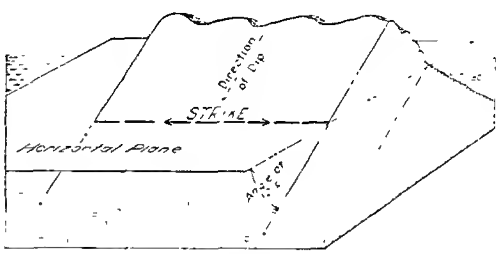


FIG. 55. A block diagram illustrating dip and strike in tilted strata.

**Dip and Strike.** In many regions, particularly in mountains like the Appalachians (including New England), the Rockies, and the Sierra Nevada, rock layers and formations are not only variously tilted or inclined, but also they show marked deviations in trend across country. Two terms are used to designate such variations in tilt and trend—dip and strike. *Dip* is the inclination of a rock layer to a horizontal plane

(or level surface). Two elements are involved, namely, *amount of dip* and *direction of dip*. By means of a compass provided with a small pendulum free to move over a graduated half-circle, amount and direction of dip are determined. Examples of note-book records would be dip 20°, S.40° W.; dip 65°, N.10° E., etc. *Strike* is the line of intersection of a dipping or tilted layer with a horizontal plane (or level surface). Or it may be defined as the direction (or trend) of a horizontal line on the surface of an outcropping rock layer. Strike is recorded thus: N.30° W., S.80° E., etc. When the direction of dip is recorded it is not necessary to give the strike because dip and strike are always at right angles, as clearly shown by Figure 55.

## Folds

**Zones of Flow and Fracture.** A *fold* is a bend in a rock layer, bed, or formation. Any rock mass, when subjected to sufficient pressure,

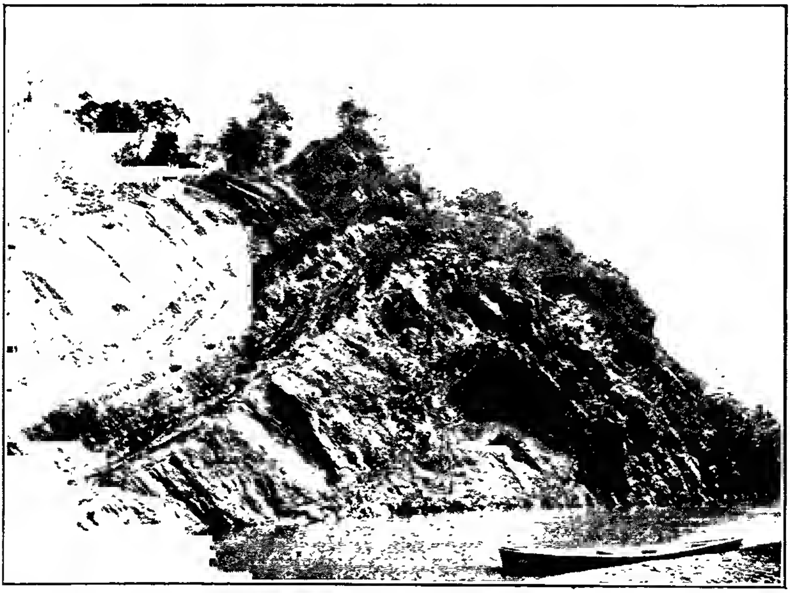


Fig. 56. An anticline in Paleozoic strata near Hancock, Maryland. (After Walcott, U. S. Geological Survey.)

or stress or strain, within the earth's crust, must either bend, flatten out, or fracture. Rock bends are folds, and fractures are joints, fissures,

or faults. Bending and flattening are both comprised under the term *rock flowage*, which means a permanent change of form of a rock by pressure, but without notable fracture. Why do rocks sometimes bend, and at other times break? The earth has, for many millions of years, been a shrinking body. Many stresses, strains, and pressures have been set up in the crustal (outer) portion of the earth as it has been adjusting or accommodating itself to the contracting interior. Due to such forces,

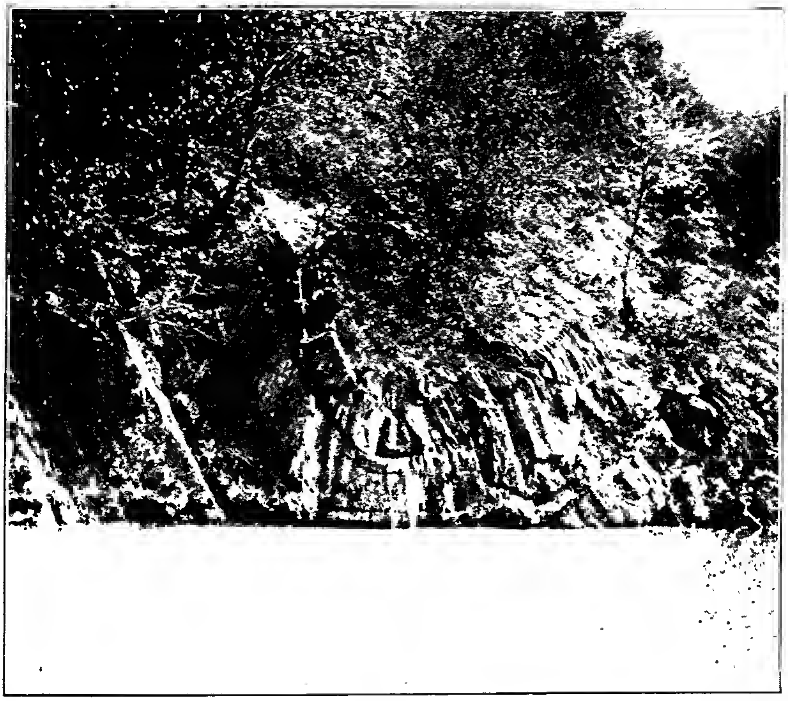


FIG. 57. A syncline near Hancock, Maryland. (After Walcott, U. S. Geological Survey.)

the rocks at and near the earth's surface have, in many places, been more or less profoundly fractured, and often subjected to sudden movements, while the rocks well within the crustal portion, that is, usually from some thousands of feet to miles down, have, in many places, been folded, or even crumpled. For such reasons the surface and near-surface portions of the crust may be, in a general way, called the *zone of fracture*, while deeper portions may be called the *zone of flow*. Rocks

(even the hardest) behave like plastic materials when subjected to great pressure well within the zone of flow, and, therefore, they bend or flatten out instead of break, because of the great weight of overlying material. This conclusion has been confirmed by laboratory experiments in which small masses of rocks have been subjected to slow, differential pressure equivalent to that which ohtains miles within the earth. Such masses have been made to change shape notably without fracture.

The idea of depth should not, however, be too much emphasized in considering the zones of flow and fracture because there are other conditioning factors. Thus, very soft, plastic rock materials like wet clay at or near the surface will readily flow under pressure, while very hard, rigid rocks like granite will usually flow only at depths of miles. Again, a very slowly applied pressure may cause a relatively hard rock to flow or bend much nearer the surface while a quickly applied pressure may cause a relatively soft rock to fracture at a considerable depth.

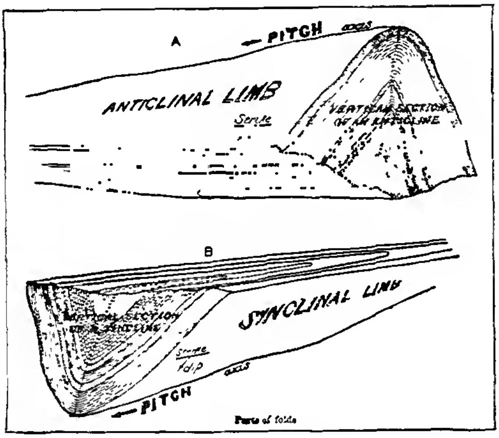



FIG. 58. Diagrams illustrating parts of folds. (After Willis, U. S. Geological Survey.)

**Kinds of Folds.** As already stated, a rock bend is a *fold*. A simple arched-up fold is an *anticline* (Fig. 56). A *syncline* is an inverted anticline, or a downbent fold (Fig. 57). The flanks of the fold are its limbs, and the crest line (or the troughline) is its *axis*. The inclination of the axis to a horizontal plane is the *pitch* or *plunge*. These features, as well as dip and strike, are all clearly represented by the accompanying diagrams (Fig. 58).

When a fold has but one limb, that is, when its layers incline in one direction only, it is called a *monocline*.

In an *isoclinal fold*, or a series of such folds, the limbs are parallel or nearly so. Such folds indicate great degrees of pressure (Fig. 60).

An *overturned fold* is one in which one limb is partly doubled under the other (Fig. 61), and a *recumbent fold* is an extreme case of over-

turning in which the limbs lie in nearly or quite horizontal position. The latter indicates great application of pressure.

The terms *anticlinorium* and *synclinorium* may be used to designate respectively, great, complex, anticlinal and synclinal structures (Fig. 62).

The term *dome* is sometimes applied to a special type of anticline in which the axis is nearly or quite reduced to zero, that is, the limbs dip downward in all directions from the top of the fold. A synclinal *basin* is an inverted dome.

Such terms as *contortions, crenulations, crumplings, plications,* or

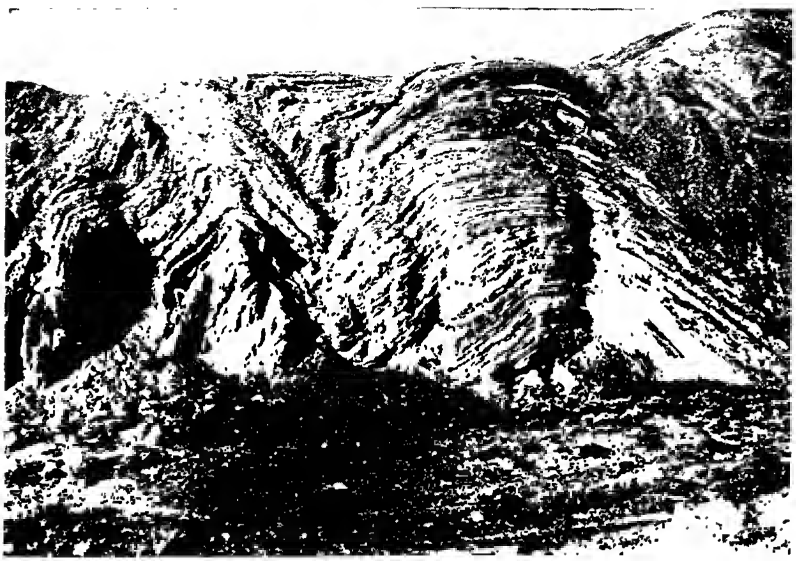


FIG. 59. Strata sharply folded into a series of anticlines and synclines. Calico Hills near Daggett, California.

*corrugations* are often applied to intense foldings of strata, especially on small scales (Fig. 63).

Under certain conditions, such as differential movement within a mass, local differences in rigidity of the rocks, etc., certain layers may become folded or contorted, while immediately adjacent layers are little or not affected.

**Examples of Folds.** Folds range in both width and length from microscopic to many miles. Most folds, especially the large ones, develop very slowly, that is, the process may require thousands, or even

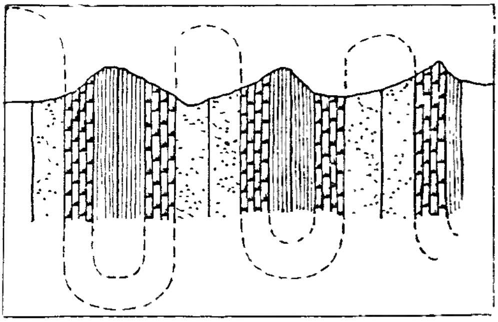


FIG. 60. Diagrammatic structure section showing isoclinal folds. (After Van Hise.)

hundreds of thousands, of years. Figure 63 illustrates small scale folds or contortions. The Uinta Range of northern Utah, many miles long and wide, is essentially a great, simple anticline whose limbs dip at very low angles. The Jura Mountains between Switzerland and France contain a series of moderately folded, symmetrical, little eroded anticlines and synclines (Fig. 197). In parts of the northern Rockies of the United States, the anticlines and synclines are considerably squeezed together and rather deeply eroded (Fig. 199). The Appalachian Mountains exhibit almost all known kinds of folds, and on almost all scales up to miles across. In Pennsylvania the rocks are less severely folded than they are in the southern Appalachians. The rocks of the Alps have been so severely folded as to give rise to an almost unbelievably complicated structure which involves various kinds of folds.

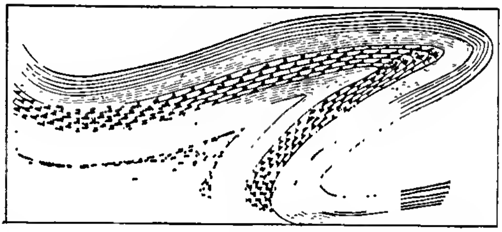


FIG. 61. Diagrammatic section of an overturned fold. (After Van Hise.)

## WARPS

The earth's crust may be gently *warped* by diastrophic forces which operate vertically, causing some areas to rise while others sink. Such movements are usually uneven, causing warped surfaces to be irregular. In all cases, however, dips of warped surfaces, or dips of warped strata or other layered rocks, are so slight as to be very locally unrecognizable. *Tilting* is a special case of warping where gentle slopes or dips are very uniform over considerable areas. Warps are usually broad, often

involving distances of 50 to many hundreds of miles, but smaller warps are not uncommon.

Willis, in his book on "Geologic Structures," distinguishes between warping and folding as follows: "In general usage the broad departures of strata from a flat attitude are called folds, as are also more pronounced bends. There is a difference, however, between the two kinds

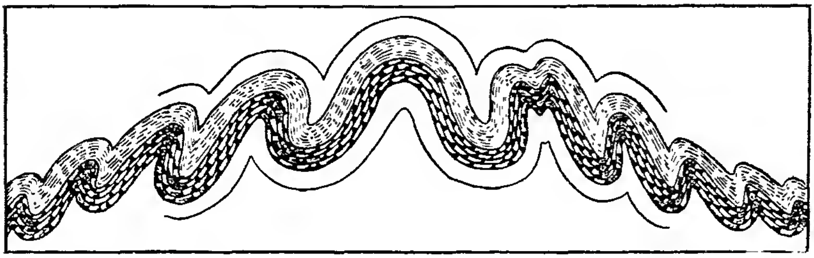


FIG. 62. Diagrammatic section of an anticlinorium. (After Van Hise.)

of forms. The broad type . . . is due to vertical movements, to subsidences, or to uplifts. The more pronounced bends, such as commonly occur as alternating troughs and arches, are caused by horizontal compression. When both kinds are designated by the same name a confusion of ideas results and may lead to wrong inference. It is better to call the effects of warping *flexures*, and to restrict the terms folding and folds to the mechanical disturbances caused by compression."

FIG. 63. Contorted strata. Los Angeles, California.

Gentle upbends are called *upwarps*, and gentle downbends are called *downwarps*.

Great upwarps, involving dimensions of scores or hundreds of miles, are known as *geanticlines*, and great downwarps of similar size are known as *geosynclines*. The latter are of particular geologic interest because at various times, and at various places, during the earth's history they have been sites of accumulation of very extensive piles of strata reaching total thicknesses of many thousands of

feet. Such sediment-filled geosynclinal basins have usually been subjected to tremendous lateral pressure, strongly folded and raised into mountain ranges.

## Joints

**Nature and Occurrence of Joints.** Almost all consolidated rock formations at and near the earth's surface are intersected by systems of fractures or cracks which divide the rocks into blocks of varying size, shape, and spacing. When very little or no displacement of their adjacent walls has taken place, such cracks are called *joints*. In many places there are at least two sets of joints crossing each other at high angles, and dividing the rock into prismatic blocks of roughly uniform shape and size (Figs. 64 and 65). In many other cases, however, numerous joints traverse rock formations very irregularly. The spacing of joints varies from a fraction of an inch to many yards. Single large joints are hundreds, and even thousands, of feet long and deep, as may often be seen in steep canyon walls and great cliffs. It seems quite certain that the whole zone of fracture of the earth is more or less jointed. Joints cannot exist below depths of approximately 12 miles because, as demonstrated by experiment, the tiniest cracks and crevices in even the hardest rocks cannot remain open under the conditions of tremendous pressure which obtain at such depths. Joints very often stand in approximately vertical positions, but they may lie in any position from vertical to even horizontal, especially when the rocks containing them have been disturbed by folding or tilting. Joint faces often are remarkably smooth and straight for long distances, particularly in fine grained, hard rocks. Joint blocks are usually fitted together tightly, but sometimes there are very per-

Fig. 64. Highly jointed plutonic rock (syenite). Near North River, New York.

ceptible spaces between them, especially if the joints have been acted upon by the weather.

**Causes of Joints.** Most joints in sedimentary, igneous, and metamorphic rocks are believed to have resulted from stresses and strains within the zone of fracture. Such joints may, on the basis of origin, be classified as *tension* and *compression joints.* When a portion of the zone of fracture is subject to differential compression or torsional strain, owing to earth contraction, the rocks tend to fracture in two general sets of joints approximately at right angles to one another very much as can be shown by experiments with glass or ice. The crest portions of folds, were not too deeply buried, are often stretched to the breaking point, resulting in systems of joints. The sudden alternation of tension and compression in the zone of fracture during the swift passage of earthquake waves is quite likely a cause of many minor joints. It is evident that relatively slight stresses and strains may cause jointing because deep, well-developed joints are often found even in large areas of horizontal strata. Tension produced by contraction during the drying-out and consolidation of sediments when raised into land also is probably a minor cause of jointing.

FIG. 65. Great joint columns 1500 feet high in sandstone. Zion Canyon, Utah.

In igneous rocks, systems of shrinkage joints no doubt often develop when the masses of molten materials contract during the process of cooling and solidification within the earth's crust.

A kind of jointing of special interest is known as *columnar structure.* It often develops by cooling and contraction of either lava flows or masses of molten material which have been forced into fissures near the earth's surface, during the process of solidification of the molten material. The effect is a splitting up of the body of rock into a system of close-fitting prisms of varying size and shape, but usually hexagonal.

They are of all sizes up to several feet in diameter, and 200 or more feet in length. The columns always form at right angles to the cooling surface, so that in lava flows they are vertical, or nearly so, and in dikes they are usually approximately horizontal. In some places this columnar structure is developed on large scales with a wonderful degree of regularity, as for example at the Devil's Postpile in California (Fig. 66); in the Columbia River Canyon; at Devil's Tower in Wyoming;

FIG. 66. Remarkably developed columnar structure in lava. Devil's Postpile, National Monument, California. (Courtesy of the U. S. Forest Service.)

and at the Giant's Causeway in Ireland. The Palisades of the Hudson near New York City are great, crudely developed, nearly vertical joint prisms 100 feet or more high.

*Sheet jointing* is sometimes well developed in massive rocks like granite and other plutonic rocks. The joints usually divide the rock into a series of crude sheets roughly parallel to the surface of the earth.

The sheets commonly range in thickness from less than a foot to about four or five feet (Fig. 67). Well below the surface a massive rock body may be in a strained condition. Removal of the overburden by

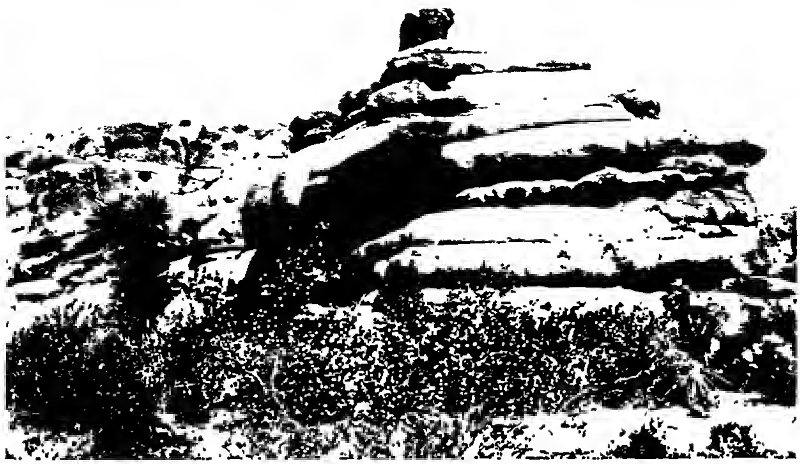


FIG. 67. Sheet jointing accentuated by weathering. Near Twenty-nine Palms California.

erosion, or even by artificial means, may relieve the strain with resultant splitting loose of successive sheets of the rock from the surface down for 50 or 100 feet or more. Such sheets are known to have broken loose suddenly in granite quarries.

## FAULTS

**Definition.** A *fault* is a fracture in the earth's crust along the face of which there has been slipping (or displacement) of the rocks (Fig. 68). The amount of such displacement varies from a fraction of an inch to many thousands of feet. Movement along a fault generally takes place suddenly, and usually involves distances up to 20 to 40 feet, or rarely even more. In great faults the displacement represents the sum-total of many relatively minor, sudden movements.

**Nomenclature of Faults.** Faulting is by no means always a simple process, and, for a reasonable understanding of the structures involved, it is necessary to know the principal terms applied to faults, particularly to the amount and direction of movements. The accompanying dia-

grams should be carefully studied in connection with the definitions below given, and this should be supplemented with laboratory studies of models and maps, and also, if possible, with field observations. The components of faulting may be most readily comprehended by considering faulted strata made up of layers of various kinds, but of course the same general principles apply to faults in any kind of rock.

The *fault surface* is the fracture along which the slipping or dislocation of the rocks occurs. It is better to call it a surface than a plane because it is seldom smooth and straight for any considerable distance.

*Slickensides* are the smoothed or scratched portions of a fault surface resulting from friction of movement of one earthblock past the other.

*Fault breccia* is the crushed, broken, and often recemented rock

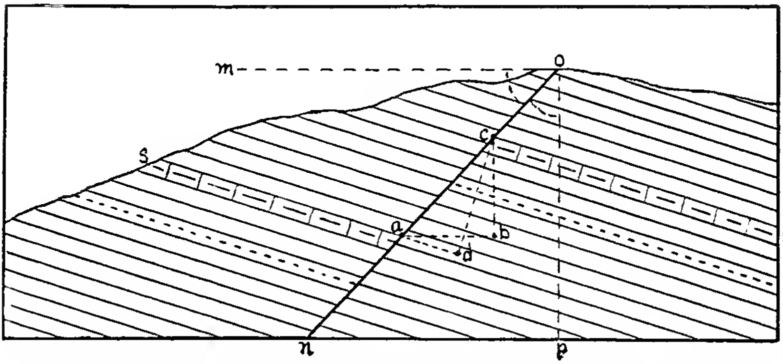



FIG. 68. Structure section of an eroded normal fault. *mon* = dip; *nop* = hade; *ac* = slip; *cb* = throw; *cd* = stratigraphic throw; *ab* = heave.

material commonly found along fault fractures, especially the larger ones, due to friction during movement. In many cases, however, faults are relatively clean, sharp breaks.

*Fault trace* or *rift* are terms applied to the trace of the fault on the earth's surface.

*Drag* is the term applied to the local bending of strata upward or downward adjacent to the fault surface according to direction of movement of the earth blocks. It is due to friction of the slipping mass along the fault. Drag is by no means always present.

Where one block of earth has moved down relative to the other along a fault, it is called the *downthrow side*, and the other is called the *upthrow side*.

Where a cliff or steep slope forms on the upthrow side as a direct result of faulting it is called a *fault scarp* (Fig. 72). Fault scarps are

almost always more or less eroded, sometimes to such an extent that no cliff, or steep slope, remains.

The rock immediately overlying a fault surface is called the *hanging wall,* and that immediately under it is called the *footwall.*

The *dip* of a fault, like that of a rock layer, is the inclination of its surface to a horizontal plane (or level surface).

The *strike* of a fault is its intersection with a horizontal plane.

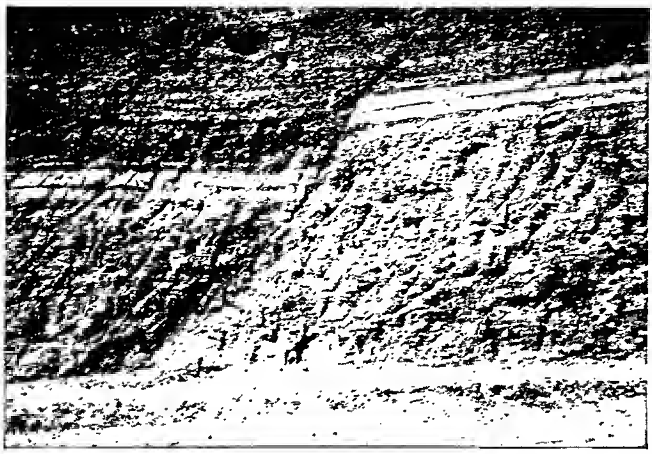


FIG. 69. A small normal fault in shale beds. The displacement is six feet. Downthrow side is on the left. Los Angeles, California.

The *hade* is the inclination of the fault surface to a vertical plane. It is always the complement of the dip.

*Slip* is the distance a rock layer has moved on a fault surface. It represents the total displacement along the fault.

*Throw* is the vertical displacement of the fractured ends of a rock layer.

*Heave* is the horizontal displacement of the fractured ends of a rock layer as measured at right angles to the strike of the fault.

*Stratigraphic throw* is the thickness of the rock layers lying between

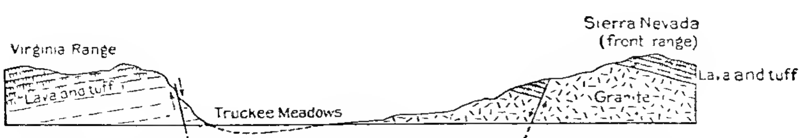



FIG. 70. Structure section of a normal fault-block (graben) which has sunk about 3000 feet in western Nevada. (After U. S. Geological Survey.)

the faulted ends of a given layer, as measured at right angles to the layers.

A *compound* or *distributive fault* consists of two or more parallel (or approximately parallel) faults close together. In such a case the displacement has been distributed instead of being concentrated along a single fault-surface.

*Step faults* may be like those of a compound fault, but they are usually farther apart, and they must all dip in the same direction (Fig. 71 B).

A *graben* or *tough fault* is a block of earth, bounded by two or

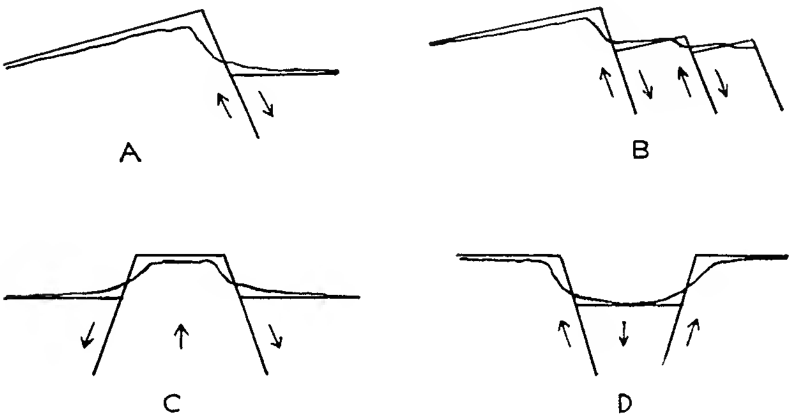



FIG. 71. Diagrammatic structure sections to illustrate various kinds of fault blocks. Straight lines show blocks as if unaffected by erosion and deposition. Other lines are profiles after erosion of high portions and partial covering of low portions with sediment. A, a tilted block; B, step-fault blocks; C, a horst; and D, a graben. Arrows indicate directions of movement.

more faults, which has sunk relative to the surrounding mass of earth (Figs. 70, 71 D).

A *horst* is a block of earth, bounded by two or more faults, which has been elevated relative to the surrounding mass of earth (Fig. 71 C).

**Kinds of Faults.** Five kinds of faults, based upon directions of movements along the fault surfaces, may be explained briefly as follows:

1. *Normal faults.* When the fault surface dips toward the downthrow side it is a *normal fault* (Fig. 72). In this case the hanging wall has slipped down an inclined fault surface relative to the footwall. Figure 72 illustrates a very simple case of normal faulting in horizontal strata as it would appear unaffected by erosion. Figure 68 represents an eroded normal fault in tilted strata. As shown by the figures,

normal faulting involves a local extension of the earth's crust because the fractured ends of the rocks have been pulled apart horizontally by an amount measured by the heave. For this reason normal faults are sometimes called *tension faults.* Normal faults usually dip at relatively high angles.

2. *Thrust faults.* When the fault surface dips toward the upthrow side it is a *thrust fault* (Fig. 72). In this case the hanging wall has been shoved, or thrust, up an inclined fault surface relative to the footwall. Figure 72 represents a simple case of thrust faulting in horizontal strata as it would appear unaffected by erosion. Generally, however, the fault scarps have been more or less obliterated by erosion. As shown by the figures, the crust of the earth is relatively shortened by thrust faulting because certain blocks of earth are partly shoved or thrust over others. For this reason thrust faults are some-

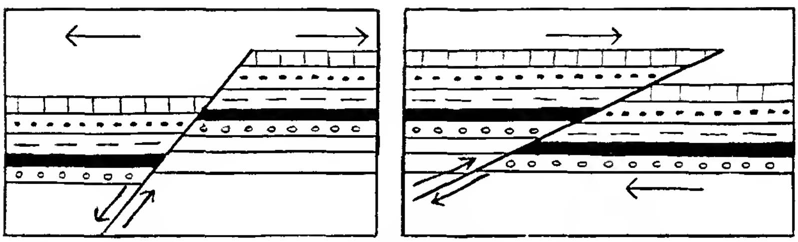


FIG. 72. Structure sections of a simple normal fault (*on left*) and of a simple thrust fault (*on right*).

times called *compression faults.* Thrust-fault surfaces are generally inclined (dip) at relatively low angles.

3. *Vertical faults.* When there has been upward or downward movement on either side of a vertical fault-surface it is a *vertical fault.* The fault surface dips 90°, or nearly so, and there is neither hanging wall nor footwall.

4. *Horizontal faults.* When the movement has been wholly horizontal, or nearly so, on either side of a fault surface (either inclined or vertical), it is a *horizontal fault.* A sudden movement of this kind of 2 to 22 feet along a fault caused the California earthquake of 1906, but fault movements of this kind are rare.

5. *Pivotal faults.* When one portion of an earth block moves upward, and another portion of the same block moves downward, on an axis at right angles to the fault, it is a *pivotal fault.* The block on one side of the fault works as though on a pivot with reference to

that on the other side. The effect is for the earth block on one side of the fault fracture to be in part upthrown, and in part downthrown (Fig. 74).

**Cause of Faulting.** The zones of flow and fracture in the earth's

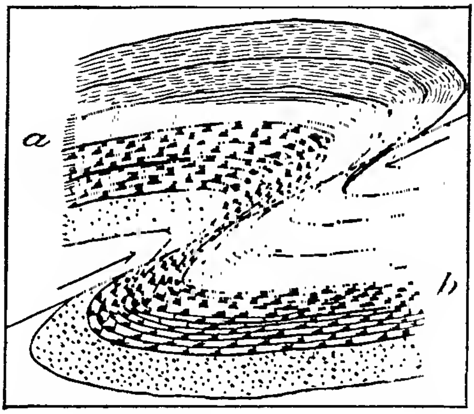



FIG. 73. A sharp fold passing into a thrust fault. (After Van Hise, U. S. Geological Survey.)

crust have already been described briefly in the discussion of the cause of folding. Rocks bend (or flow) when subjected to sufficient stress or strain in the zone of flow, while the same forces cause them to break in the zone of fracture. Every fault must, therefore, die out downward

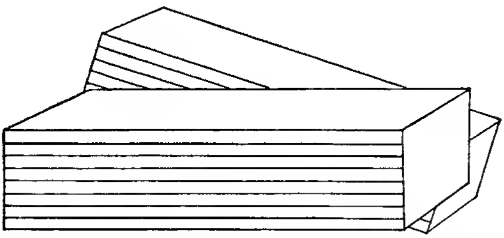


FIG. 74. Block diagram showing the principle of the pivotal or rotational fault.

because the fracture grades into material which yields without breaking. The forces which cause faulting are compression, torsional strain, or tension (stretching) in the outer crustal portion of the earth. Any such force may be exerted upon a rock mass until its breaking point is reached, when a fault results, usually accompanied by sudden movement. This movement relieves the force for a time, but the latter may

increase slowly again to cause renewed movement along the old fracture, and so on repeatedly.

The *ultimate cause* of faulting, as for that of folding, is a more difficult and uncertain matter, but by many geologists, including the author, it is believed to be intimately bound up with a shrinking earth, in the outer or crustal portion of which tremendous stresses and strains are, and for countless ages have been, set up.

**Topographic Influence of Faulting.** Many relief features of the earth, both great and small, are direct or indirect results of faulting.

FIG. 75. Part of the scarp of the great Hurricane fault. The scarp, 2000 feet high, has been moderately affected by erosion as shown by Figure 76. About 30 miles south of Cedar City, Utah.

If a considerable fault movement of any kind, except horizontal, should suddenly take place, a cliff or steep slope, called a *fault scarp*, would develop on one side of the fault (Fig. 72). Sudden movement of this kind is, as we have already learned, the most common cause of earthquakes. A single movement rarely produces a scarp more than ten or twenty feet high, but many repeated movements along the same fault may develop a scarp thousands of feet high, as along the eastern face of the southern Sierra Nevada (Fig. 105). Even while such a scarp is developing through many thousands of years of time, the processes of weathering and erosion set to work to cut it down and diminish its

steepness. Such eroded fault scarps are common in many parts of the world.

In the course of time both sides of a fault, including the scarp, may be brought to the same level by erosion. If, then, the rock on the upthrow side is weaker than that on the downthrow side, and the whole region should be elevated, erosion would be renewed and the weaker rock would be worn down faster, causing a scarp to develop on the original downthrow side. Or, if the weaker rock should lie on the downthrow side, the scarp would again develop on the upthrow side. Scarps thus formed by erosion along faults are called *fault-line scarps* by Davis to distinguish them from true fault

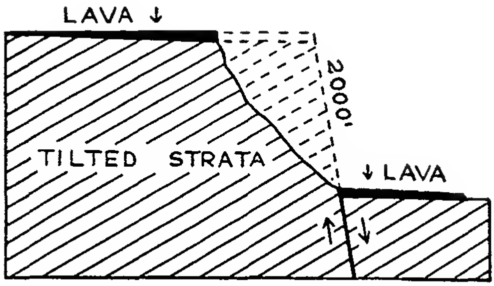



FIG. 76. Structure section through the Hurricane fault scarp pictured as Figure 75. The lava fields were continuous before the dislocation. The broken lines show the amount of erosion.

scarps. Fault-line scarps are common in the eastern Adirondack and Mohawk Valley regions of New York State.

Thrust faulting also often causes great and small changes in topography. Thus the whole eastern face of the Rocky Mountains in Glacier Park, Montana, is the front of a vast earth block several thousand feet high which has been shoved upon the Great Plains from the west. This fault scarp has been considerably cut into and indented by the action of rivers and glaciers.

Thrust fault scarps, like normal fault scarps, may be, in the course of time, cut away and fault-line scarps developed instead.

## UNCONFORMITIES

When strata are deposited in uninterrupted succession, layer upon layer, they are said to be *conformable*. Often, however, there is a break or interruption in the succession of strata which is usually indicated by

the fact that one set of strata rests upon the eroded surface of another set. In many cases strata rest upon the eroded surfaces of igneous or metamorphic rocks. The interruption may much more rarely be due

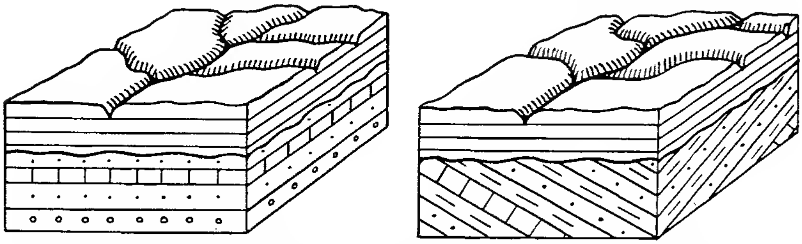


FIG. 77. Block diagrams to illustrate a disconformity (on the left) and a nonconformity (on the right). The heavy irregular line marks the erosional surface or unconformity.

simply to lack of deposition of sediments for a time, with no accompanying erosion. Sets of rocks whose regular succession is thus inter-

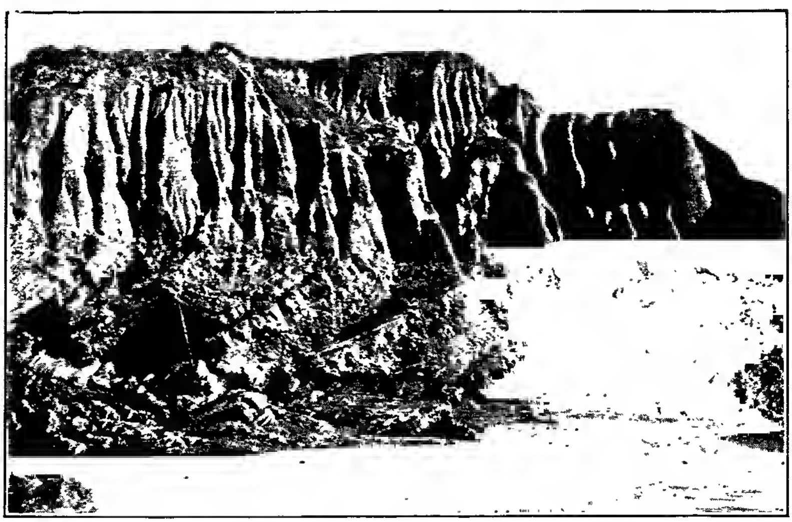


FIG. 78. A conspicuous unconformity. Horizontal sands and gravels of Quaternary age resting upon tilted and eroded Tertiary shales. Near Port San Luis, California. (After G. W. Stose, U. S. Geological Survey.)

rupted are said to be *unconformable*, and the structure is called an *unconformity*.

A mass of stratified sediments may be raised out of water and tilted, folded, or left practically horizontal, and then eroded. Submergence

would allow new sediments to deposit unconformably upon the eroded surface. Renewed uplift and partial erosion may lay bare such an unconformity as illustrated by Figure 78 in which the underlying strata have been highly tilted and eroded, and by Figure 203 in which the underlying strata have been notably folded and eroded.

If the upper series of beds rests upon the eroded surface of tilted or folded strata, or of non-stratified rocks (igneous or metamorphic),

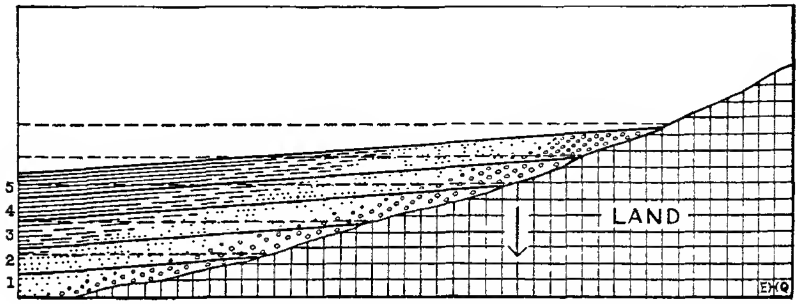



FIG. 79. Diagrammatic section showing the principle of overlap. Horizontal broken lines represent different stages of sea level relative to the land. As the sea encroached toward the right upon the subsiding land, deposition of the sediments 1, 2, 3, 4, 5, extended farther and farther to the right, later formed beds thus overlapping earlier formed beds.

there is a very obvious unconformity called a *non-conformity*. If, however, two sets of beds separated by an erosion surface have their stratification surfaces practically parallel, there is a more or less deceptive unconformity called a *disconformity*.

A special phase of unconformity is known as *overlap* in which the younger (overlying) strata extend farther, that is, they cover a wider area, than the older (underlying) strata, and so overlap the latter. Overlap will develop when strata accumulate upon a sloping area gradually subsiding under water.

## Modes of Occurrence of Igneous Rock

**Plutonic and Volcanic Rocks.** In even an elementary discussion of the arrangement (structure) of the rocks of the earth's crust, the modes of occurrence of the igneous rocks must be considered. Igneous rocks represent either molten materials which have been forced into the crust of the earth to cool and solidify below the surface, or molten materials, or fragments of once molten materials, which have been forced out upon the surface of the earth. The former are known as *plutonic*

or *intrusive* rocks, and the latter as *volcanic* or *extrusive* rocks. Studies of igneous rocks in many parts of the world have shown that plutonic rocks are of far greater volume than volcanic rocks. Plutonic rocks become exposed at the surface only as a result of erosion of the rocks which formerly covered them. Volcanic rocks are, no doubt, generally connected with deep-seated plutonic masses through intermediate rocks, reservoirs of molten masses of the latter having always, or nearly always, been the sources of the volcanic materials.

**Modes of Occurrence of Plutonic Rocks.** *Dikes.* A *dike* is a mass of igneous rock which, in a molten condition, was forced into a fissure in the earth's crust and there consolidated. Dikes vary in width from less than an inch to several hundred feet, and in length commonly from a few feet to 10 or 20 miles. One in England is about 100 miles long. Dikes are very abundant, a few among many regions being along the

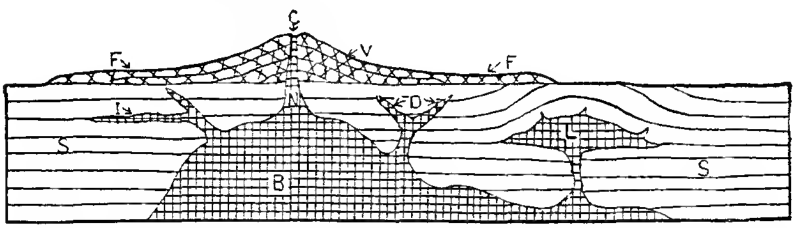



FIG. 80. Diagrammatic structure section illustrating modes of occurrence of igneous rocks. $S$ = strata; $B$ = batholith of plutonic rock; $L$ = laccolith; $D$ = dikes; $I$ = intrusive sheet or sill; $V$ = volcano; $N$ = neck of volcano; $F$ = lava flows; $C$ = crater.

coast of Maine; Cape Ann in Massachusetts (Fig. 81); and at Spanish Peaks in Colorado (Fig. 82). Dikes may be partially glassy, fine grained crystalline, or coarse grained crystalline, depending on the size, rate of cooling, etc., of the injected molten masses. They are sometimes arranged in roughly parallel groups, but often they form irregular, branching networks cutting through rocks of any kind.

*Sills.* Where a mass of molten material (magma) has been forced as a sheet or layer between beds of strata, or along foliation surfaces of metamorphic rocks, it cools to form a *sill* or *intrusive sheet.* A sill is, therefore, a special kind of dike. Sills vary in thickness from less than a foot to hundreds of feet, and they commonly extend laterally from a few acres to many square miles. An excellent example is the sill in the Hudson Valley near New York City, the outcrop of which is called the Palisades of the Hudson, in part forming a bold cliff several hundred feet high, facing the river for 30 miles.

*Laccoliths.* A *laccolith* is a dome-shaped mass of igneous rock which, in molten condition, has been forced between strata, causing the overlying rock layers to be domed or arched up. It has a more or less flat floor. The magma rising into the earth's crust through a relatively small opening becomes such a stiff fluid (or so viscous) that it can no longer penetrate the strata, so it spreads between them, and arches up the overlying beds (Fig. 80). Laccoliths commonly range in thickness from a few hundred feet to a mile in the middle, and in diameter from hundreds of yards to several miles. The Henry Mountains of

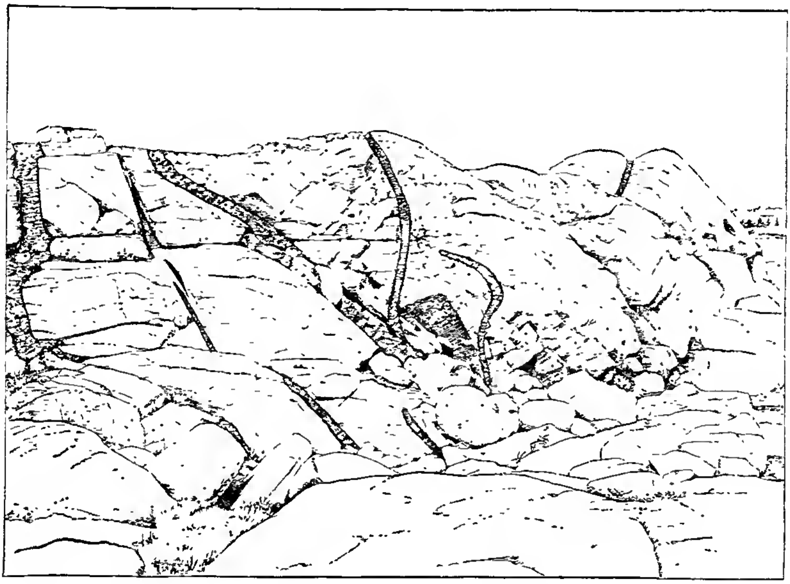


FIG. 81. Basaltic dikes in granite. Cape Ann, Massachusetts. (After N. S. Shaler, U. S. Geological Survey.)

southern Utah consist of a series of laccoliths showing all stages of removal of the overlying, arched up strata. Various others occur in Utah, Colorado, Montana, and South Dakota. Bear Butte in South Dakota (Fig. 83) is a very fine example of a large laccolith whose cap rock has been almost completely removed, leaving only the upturned edges of the strata as a ring around its base.

*Volcanic necks.* A *volcanic neck* is the hardened lava which fills the feeding channel (or conduit) of a volcano. It is roughly cylindrical in shape, and it commonly varies in diameter from a few hundred feet to a mile or more. Long continued erosion may finally cut away most of

the relatively looser material of the volcano, leaving much of the core or neck of the mountain standing out in bold relief. There are excellent examples in New Mexico (Fig. 177) and Arizona, and in parts of Great Britain and France.

*Stocks or bosses.* The term *stock* (or *boss*) is applied to a fairly large body of plutonic rock, with crudely circular or oval ground-plan, which, in molten condition, was forced into the earth's crust by cutting

FIG. 82. Vertical dikes cutting strata and standing out in bold relief as a result of erosion. W. Spanish Peak, Colorado. (After G. W. Stose, U. S. Geological Survey.)

across the enclosing rock. Stocks usually increase in diameter downward. They vary in diameter from hundreds of feet to a number of miles. They are very common in New England and in the Piedmont Plateau of the eastern United States.

*Batholiths.* These are also called *bathyliths.* In all important respects, except size, they are like stocks. They extend over areas of hundreds, to many thousands of square miles, as for example in the southern Sierra Nevada Range; parts of the Rockies; eastern Canada; the Adirondack Mountains; New England; and the Piedmont Plateau. Stocks and batholiths, being true plutonic rocks, are of course exposed

at the surface only as a result of profound erosion of the overlying rocks. Granite, syenite, and gabbro are very commonly the rocks of stocks and batholiths.

**Modes of Occurrence of Volcanic Rocks.** *Lavas.* Streams and sheets of molten materials (lavas) may pour out of volcanoes or fissures in the earth and cool to be successively covered by later flows. In

FIG. 83. A laccolith unroofed by erosion. The upturned strata around its base formerly extended completely over the igneous body. Figure 54 shows it as represented by a geologic map and a structure section. Bear Butte, South Dakota. (After N. H. Darton, U. S. Geological Survey.)

such a manner a lava field may be built up to a thickness of hundreds, or even thousands of feet, and an extent of many square miles.

*Fragmental materials.* Through successive explosive eruptions of volcanoes, fragments of lava may be ejected in great quantities and scattered near and far. Thick and extensive beds of such materials, ranging in size from the finest dust to blocks weighing tons, may be built up. Both lavas and fragmental materials are more fully described in Chapter XI.

## CHAPTER VII

## THE WORK OF STREAMS

### Introduction

**Erosive Importance of Streams.** All things considered, running water is the most important of the three great agents of erosion—water, wind, and ice. About 30,000 cubic miles of water (partly in the form of snow) fall yearly upon the lands of the earth. Approximately one-fifth of this tremendous quantity of water is carried by streams into the sea each year. Some idea of the enormous amount of energy developed by these streams may be gained from the fact that they make an average descent of nearly one-half of a mile, this being the average altitude of the lands of the earth. A very considerable amount of energy is also developed by streams of desert regions which do not enter the sea. Much of this stream energy is used up in friction, in wearing away rock materials from the bottoms and sides of their channels, and in transporting sediment.

FIG. 84. Effects of rain wash upon slightly consolidated beds. Near Laguna, California.

**Rain Wash.** Rain water accomplishes a certain amount of erosion before it collects into definite streams. Everyone is familiar with the fact that soils are carried down slopes by the wash of the rain. When rain "flows off in a sheet, as on a smooth surface, the depth of the water is slight, the flow not very swift (unless the slope is very steep), and the wear correspondingly slight. Such wear is called *sheet erosion*" (Chamberlin and Salisbury).

Where rain falls upon soft or loose material such as clay or sand, especially where the slopes are steep, the effect of rain wash is much more pronounced than where it falls upon hard rocks (Fig. 84). A mantle of vegetation of course tends to protect soils and rocks against rain wash.

## How Streams Erode

Erosion is, as we have already learned, a rather complicated process carried on by either water, wind, or ice, and it consists of a number of sub-processes such as weathering, corrasion, solution, pressure, and transportation. Stream erosion involves all of these sub-processes. Weathering has already been dealt with in Chapter V. It is the present purpose to consider corrasion, solution, and pressure as factors of erosion, reserving the fuller discussion of stream transportation for a separate, important heading just beyond.

**Corrasion.** Surfaces of hard rocks are only very slightly worn mechanically by clear water flowing over them. A remarkable case in point is the constant rush of the mighty volume of clear water over the crest of Niagara Falls. The water is clear because it comes out of Lake Erie which acts as a settling basin for sediment. In spite of the velocity of the water, myriads of tiny, growing plants (algae) are attached to the rocks at the very brink of the falls, proving that any mechanical wearing away of the rocks must be very slight. The same principle is illustrated by many very clear streams with even rather swift currents which emerge from lakes, and whose sides and bottoms may be lined with moss or other vegetation.

In cases of streams of at least moderate velocity and properly supplied with tools, mechanical erosion becomes very pronounced. The tools are rock fragments of all sizes from those of silt, mud, or sand to pebbles or even boulders. By *corrasion* is meant mechanical wearing away of rocks by the rubbing, grinding, and bumping action of rock fragments carried by any agent of transportation—water, wind, or ice—against the bottom and sides of the channel, and also against themselves. We are here concerned with the corrasive action of streams only, corrasion by ice and wind being considered in succeeding chapters.

From the above statements it may be readily understood that the factors which facilitate rapid corrasion by streams include swift current, a liberal supply of tools (especially of angular fragments of hard rocks and minerals), and relatively soft or weak rock over which the water

flows. Since the tools themselves are worn in the process of corrasion they soon become rounded. This is true of all sizes of rock fragments from the tiniest to big boulders (Fig. 85).

**Solution.** We have already learned that many rocks and minerals are more or less soluble in water, and that their solubility is increased by the presence of small amounts of carbonic acid gas and oxygen which are found in all water in nature. Limestone is, of all the very common rocks, most susceptible to solution, being in fact completely soluble when perfectly pure. Although the process is a slow one as measured

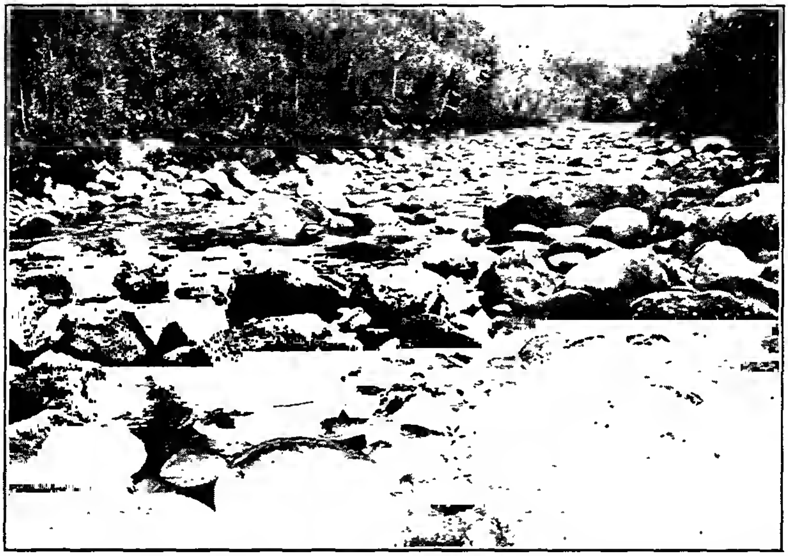


FIG. 85. Tools with which a river works. Boulders in the bed of a river at time of low water. Near Wells, New York.

by the span of an ordinary human life, nevertheless a stream of even moderate velocity flowing over bedrock of limestone, or even impure limestone, carries away a large amount of the rock in solution in a short time, geologically considered. The cutting of the valley into the crust of the earth is, under such conditions, notably facilitated. Where a stream flows over a hard igneous rock like granite, the work of solution is very much less effective because the quartz in this rock is scarcely, if at all, affected, while some of the feldspar material goes into solution only very slowly. As a result of rain wash over the ground, and on gully or valley sides, more or less mineral matter is taken into solution and carried into streams. A large river like the Mississippi carries a

tremendous amount of dissolved mineral matter into the sea each year. This phase of the subject is treated a little beyond in this chapter.

**Pressure.** The mere impact or pressure of running water may, under certain conditions, effect a considerable amount of erosion. Thus a stream of relatively clear water, flowing through soft or loose material, may by this process cut back its bank, or push off material from the bottom of the channel. But even where rocks are hard they are very commonly intersected by numerous cracks (so-called *joints*), causing the rocks to be more or less separated into angular blocks. In sedimentary rocks the stratification surfaces are often also a factor in dividing rock masses into blocks. In many places such joint blocks are only loosely attached to the parent ledge, especially where various agencies of weathering have acted along the joint cracks. Many loosely attached joint blocks of this kind are removed by the mere pressure of the current flowing against them.

FIG. 86. A detail view of the runaway Colorado River cutting back banks of soft, deep loamy soil as it rushed through the Imperial Valley, California, between 1904 and 1907. (Photo by U. S. Geological Survey.)

**Transportation.** A process essential to erosion is transportation, for, unless the rock materials which enter streams are carried away, there can be no wearing down of the land (erosion). This important process of erosion is separately considered a little beyond.

**Influence of Joints.** Mention has already been made of the influence of joints in aiding streams to push off blocks of rocks from ledges by mere impact of the current. Where running water enters joint cracks in the sides or bottom of a channel, the work of solution is increased because much larger surfaces of rock are exposed to the action. In limestone or limy rocks, joint cracks are often so enlarged by solution that the joint blocks become easy prey to the pressure of the current which pushes them away.

The work of corrasion is also made more effective by joints, particularly where they have been enlarged by solution, or by other weathering agencies, because more rock surfaces are then exposed to corrasive action along the bottom and sides of the channel.

## Transportation by Streams

**The Stream Load: How it is Carried.** All the material carried by a stream constitutes its *load*. The visible load consists of materials carried in suspension and rolled on the bottom, while the invisible load is the mineral matter carried in solution. What are some of the sources of the visible stream load? This question may be readily answered by following a typical, small, swift stream, especially in time of flood, through its valley for a few miles, or even less. Materials are carried down the valley sides or slopes by rain-wash, or by water from melting snow; landslides and avalanches, as well as the slower movement of hillside creep contribute considerable quantities of rock fragments of all sizes; loose deposits of clay, sand, gravel, and even boulders, through which the channel is being cut, easily become part of the load; solid rock of the valley walls, where undercut by the current, falls into the stream; joint blocks of both bottom and sides of the channel may be pushed off by the pressure of the current and become part of the load; and many fragments are supplied by the process of corrasion on the sides and bottom of the channel.

Much of the material in solution (invisible load) is supplied to streams by underground waters where they emerge as springs in the stream valley; some is added as a direct result of the solvent action of rain water on the valley sides; and some is taken into solution by the stream itself from the rocks over which it flows.

The water in a stream does not move as a simple forward current, but rather it is subjected to very complicated motions including the main current forward, upward and downward movements, and "eddies" and

"boils." The secondary upward currents bring the finer rock fragments (sediment) into suspension by carrying them up from the bottom of the stream. The coarser, heavier rock fragments are either pushed or rolled along on the bottom of the stream by the current.

**Law of Transportation.** Even a moderate increase in the velocity of a stream increases almost incredibly its power to transport rock débris. According to a well-established law of running water, *the transporting power of a current varies as the sixth power of the velocity.* Thus a current which is just able to move a rock mass of a given size will, when its velocity is only doubled, be able to transport a mass of similar rock 64 times as large because 2 raised to the sixth power is 64. This is easily demonstrated in a simple way as follows: A current with a certain velocity can just move along a cubic inch of rock in the form of a cube. Now a cube of rock 64 times as large has 16 square inches on each face. When the velocity of the current is doubled it is evident that twice as many particles of water must strike each of the 16 square-inch surfaces of the larger block with twice the velocity or force. Accordingly, 64 times as much force must be exerted against the face of the larger block, or just enough to push it along. Since the sixth power of 3 is 729 it follows, according to this law, that by trebling the swiftness of the current its transporting power is increased 729 times!

When a stream rises very rapidly during a cloudburst, or when a dam suddenly gives way, the water rushes down a valley with high velocity. An understanding of the remarkable law of transportation helps us to comprehend why, under such circumstances, the water does so much damage, carrying along massive bridges, big boulders, and even locomotives.

In all of our considerations of stream transportation, it should of course be borne in mind that, due to the buoyant action of water, a mass of average rock with a specific gravity of nearly three loses about one-third of its weight when immersed in water. This greatly facilitates the transporting power of currents.

**Graded and Overloaded Streams.** Most streams have sufficient velocity and volume to transport more material than is fed into them from tributary slopes and streams. Such a stream, therefore, has energy left to cut down its channel, that is, to *degrade* it. As the down-cutting process goes on, the *gradient* (or declivity) of the stream bed becomes more and more gentle until a condition is reached in which the whole energy of the stream is used up in transportation, and then degradation ceases.

Some streams are unable to transport all the material which is fed into them. They are said to be *overloaded.* Not only does such a stream lack power to cut down its channel, but it actually deposits part of its load and so builds up its channel, that is, *aggrades* it. In certain cases, where such aggradation goes on, the gradient of part of a stream (e.g. Platte River, Nebraska) may gradually become steeper until the stream is there able to transport its whole load.

A stream which has reached the balanced condition between down-cutting and deposition is said to be at grade. In other words, a *graded* river is one which, on the average, neither degrades nor aggrades, but is just able to carry the load supplied to it from tributary slopes and streams. Because of varying conditions, portions only of a stream may be temporarily graded. Also, a graded stream may degrade its channel during times of flood, while during times of lower water it may deposit, but it is the average condition which should be considered.

**Amount of Material Transported.** Within the lifetime of a human being, the ordinary river seems to accomplish little or nothing by way of enlarging its valley. Within a relatively short part of geologic time, however, a large valley, or even a great canyon, may be carved out (eroded) by a stream. Thus, what is now the space occupied by the whole Connecticut Valley of western New England was once filled by a mass of solid rock which, during the present (Cenozoic) era of geologic time, has been weathered and eroded, and the resulting materials carried away by the Connecticut River. Or again, the mighty Grand Canyon of Arizona has been formed since the middle of the present era as a result of the removal of a body of rock hundreds of miles long, 8 to 15 miles wide, and thousands of feet thick (Fig. 112). So it is with nearly all of the valleys and canyons of the world because with relatively few exceptions, they have been carved out by the eroding and transporting power of the streams which they contain. It is, as would be expected, a general rule that the larger valleys are occupied by the larger streams.

According to a good estimate, more than 800,000,000 tons of material in suspension, solution, and rolled along are carried annually by the rivers of the United States into the sea. Some conception of the amount of this material may be gained from the fact that a train of ordinary freight cars long enough to contain it would reach around the earth at the equator more than six times!

The Mississippi River drains more than one-third of the area of the United States proper. As a result of careful observations and tests it is known that this great river discharges annually about 577,000,000 tons

of material into the Gulf of Mexico. About two-thirds of this is material in suspension, about one-fourth is material in solution, and about one-twelfth is rolled or dragged along the bottom.

## Rate of Erosion

**Rate of Erosion of the Mississippi Basin.** All lands are being more or less cut down (eroded) by streams, and estimates of the rate at which certain rivers are lowering their drainage basins have been made. As a result of measurements and tests near the mouths of these rivers, the load of material carried yearly in suspension, and rolled along by each of them has been determined. Since the burden represents rock material which has been removed from the whole drainage basin of a given stream, and the area of the basin is known, it is easy to calculate how thick a layer of this material of uniform depth would be if spread over the whole basin. The result of course represents the average yearly rate at which the drainage basin is being eroded. Data regarding the Mississippi River are unusually accurate. The area of its drainage basin is 1,265,000 square miles. As a result only of the material carried in suspension and solution, the Mississippi Basin is being lowered at an average rate of one foot in approximately 6120 years (U. S. G. S. Water-Supply Paper 234). Considering also the amount of material rolled along the bottom of the river, the drainage basin of the mighty river is being lowered at an average rate of one foot in from 5000 to 5500 years. Although it should be understood that this figure is the result of only an estimate, it is nevertheless probably accurate to within 10 per cent, and thus gives a good idea of the order of magnitude of the rate of erosion by the Mississippi River. In regard to rate of stream erosion, the Mississippi is probably not far from the average for the streams of the world which enter the sea. Some, however, erode much faster, and others much more slowly.

## Valley Development by Streams

**Most Valleys Formed by Stream Erosion.** Nearly all streams flow in more or less well-defined valleys. Most of these streams by far flow through valleys which have been carved out by the erosive work of the streams. Some reasons for so believing are that valleys vary in size according to the size of the streams which occupy them, that is, the larger the valley the larger the stream in it; tributary streams and valleys are smaller than the ones they join; a vast majority of tributary

valleys and their streams enter larger valleys at accordant levels, that is, at the same elevation as the floors of the larger valleys; and many streams, aided by ordinary processes of weathering, are definitely known to be deepening and widening their valleys.

Some valleys were, however, ready-made for the streams which occupy them. These are usually *structural valleys*, so-called because they have been formed by earth-crust movements (*diastrophism*).

**How Stream Valleys Begin.** A new land surface formed in any manner, as for example by the draining of a lake, or by the uplift of land (out of the sea in many cases), soon has a drainage system established upon it. Water from rainfall or melting snow does not flow uniformly over the more or less uneven new surface, but it very soon tends to concentrate in the depressions, and begins to run off in streams. These initial streams begin to carve out *gullies* which, with every fresh supply of water, become deeper, longer, and wider. After a time the gullies are large enough to be called *valleys*. Many gullies may start on a new steep slope, but as time goes on certain of them become wider and take in smaller adjacent ones, and so relatively few of the original gullies really ever become valleys of considerable size.

Not all stream-cut valleys have started their development in the form of gullies. Thus over a great portion of northern North America the vast glacier of the Ice Age (Fig. 339) left widespread, irregular accumulations of rock débris over large portions of the area from which it retreated by melting. "Large parts of the surface were left without well-defined valleys, but with numerous lakes (e.g. Wisconsin and Minnesota). The rainfall of the region was enough to make these lakes overflow. Where a lake overflows, the outgoing water follows the lowest line accessible to it, so long as there is a line of descent. In this case, the running water will start to cut a valley all the way from the lake which furnishes the water to the end of the stream, at the same time. No part of such a valley is much older than another." (R. D. Salisbury.) Such a valley is of course not a grown-up gully.

**How Valleys Lengthen.** Water which flows into the upper end of a gully or valley cuts back its head by erosion. By such a process of *headward erosion*, a gully or valley is lengthened. A valley head is seldom cut back (lengthened) in a straight line. One reason for this is that differences in the character of the rock material cause headward erosion to proceed more easily in some places than in others. Another is that irregularities of the surface cause the water which flows into the head of the gully or valley to be concentrated first in one position and

then in another. For such reasons the headward erosion proceeds irregularly, and thus the crookedness of so many valleys is accounted for.

If a large spring is located at the head of a valley, the dissolving and undermining action of the spring water may aid headward erosion considerably by recession of the spring head.

The lengthening of a valley ends when a permanent *divide* (division of drainage) is developed, because then the amount of erosion on one side of the divide is counterbalanced by that on the other side.

**Valley Deepening: Base Level.** A valley is deepened by the cutting down (degradation) of its floor by the erosive action of the stream which flows through it. As time goes on, and if no other process intervenes, the power of a stream to cut down (degrade) its valley gradually diminishes, because of lessening velocity, until a limit is reached below which it cannot degrade. The limit is the level of the sea, lake, or valley floor into which the stream empties, but obviously only the lower course of the valley can ever actually reach the limit because there must be at least a slight slope (*gradient*) farther up the valley in order that the stream may continue to flow. The lowest level to which a stream can cut down (degrade) its valley bottom is called *base level.* In this connection it should be remarked that the channel of a stream may be actually a little below the level of the standing water into which it flows. Thus at and near the mouth of the Mississippi the *channel* of the river is as much as 100 feet below tide water because the current of the mighty river is able to keep its channel scoured to that depth as it rushes into the Gulf of Mexico.

**How Valleys Widen.** Most valleys are much wider than the streams which flow through them, but it by no means follows that the streams were ever necessarily wider or larger than they now are. If a valley developed wholly by the down-cutting action of a stream, the valley would be no wider than the stream, and its walls would be vertical. This latter type of valley (or rather gorge) is approached where all conditions for down-cutting are so favorable that they greatly predominate over other factors which operate to widen the valley. An excellent case in point is the upper end of Zion Canyon, Utah, which is over 2000 feet deep with nearly vertical walls which are in places not more than 100 to 200 feet apart at the top (Fig. 88).

Some of the ways by which the great majority of valleys are made wider across their tops are the following: Loose, weathered materials are washed down the valley sides by rain. If the slopes are steep, some materials roll down, and loose materials especially when they are soaked

with water, may *creep* or *slump* to lower levels. On steep slopes, rock material may move down suddenly in the form of *landslides*. Talus piles accumulate at the bases of very steep valley walls as a result of weathering. Materials which move to the bottoms of the valley sides in these and other ways are usually carried away by the streams in the valleys, and thus the tops and sides of valleys which are occupied by actively down-cutting streams steadily become wider. Then, too, since streams are rarely if ever straight, the current in many places strikes one side of the channel with greater force than the other. Thus, while

FIG. 87. A meandering stream in a small valley. South Russell, St. Lawrence County, New York.

a stream is cutting its channel deeper, it is also doing some direct work of lateral erosion, and so widening its valley at the bottom. Valley widening of this kind is, however, mostly accomplished by streams at or near grade as will next be explained.

**Lateral Erosion: Meanders, Oxbows, and Flood Plains.** Some work of lateral erosion is accomplished by rather actively down-cutting streams, as just explained, but the most effective work of this kind is done by streams with relatively low velocities and little or no down-cutting power, that is, by streams at or near a graded condition. Such a stream may flow upon an original nearly flat surface, or in a valley, or portion of a valley, where a graded, or nearly graded, condition has

been reached. In a slow-moving stream of this kind, the current is easily turned against one side or the other of its channel. This may be brought about where the swifter current of a tributary enters, or by some obstacle like a rock, or where the material of one bank is more easily eroded than that on the opposite side.

If for any reason the main current of a slow-moving stream strikes with greater force against one bank, it will be eroded sidewise, and from there the current will be deflected against the opposite bank somewhat farther downstream, causing lateral erosion to take place there. By a continuation of such a process, with the points of attack shifting downstream little by little, a series of sweeping curves called *meanders* develops (Fig. 93). Such meanders become more and more pronounced as a graded condition is approached by the stream, and they finally become a series of loops mostly separated by only narrow necks. Finally the necks are cut through one by one, and cut-off meanders, called *oxbows*, are formed, marking the old channel Meanwhile other meanders and loops develop.

FIG. 88. A very narrow, steep-sided canyon 1500 feet deep. The Narrows, Zion Canyon, Utah.

Wide flats, called *flood plains* (Fig. 94) because they are flooded at times of high water, are developed by this process. The lower reaches of some great rivers, as for example the lower Mississippi River, have developed flood plains 20 to 75 miles wide, and hundreds of miles long. Farther and farther upstream the flood plains usually become less and less prominent. Meanders and oxbow lakes are wonderfully developed on large scales for several hundred miles over the flood plain of the lower Mississippi River. The oxbow lakes are there called *bayous*. Oxbow lakes gradually

fill with silt and vegetable matter first to form marshes and finally meadow land.

**Tributary Valleys: River Systems.** In most cases by far a valley has other valleys tributary to it, and these in turn branch repeatedly into smaller and smaller tributaries. Tributary valleys usually begin as gullies on the sides of the main valley of a region either where the rocks are of uniform hardness, but where rain water moving down the slopes tends to concentrate somewhat more along certain paths than others, and hence to erode faster there, or where the materials of the slopes are locally weaker and hence more easily eroded. A gully once

FIG. 89. The oxbow of the Connecticut River near Northampton, Massachusetts, formed in 1841.

started by such a process develops into a valley on the sides of which other gullies form until, under ordinary conditions, a whole system of branching valleys covers a region. A *valley system* thus comprises a main valley with all of its tributary valleys, while a *river system* comprises a main stream and all of its tributary streams. The whole area drained by a river system is called a *drainage basin.*

**Accordance of Tributary Valleys.** In normal valley and river systems, it is almost always true that a tributary enters its parent valley and stream at grade, that is, at the same elevation as the main stream. Such streams and valleys are therefore said to be *accordant.* In a river

system which is very actively degrading its valleys it might be presumed that tributaries, with their smaller volumes of water, would not be able to cut down the lower ends of their valleys as fast as the main streams into which they flow. The fact is, however, that, as a main stream sinks its channel, the slope or gradient at and near the mouth of the tributary stream is increased enough to enable the latter, through its augmented velocity, to cut down as fast as the main stream in spite of lesser volume.

In cases where main valleys have had their sides (especially toward the bottom) cut back and steepened by glacial erosion, or where they have been interfered with by certain other processes, tributaries may enter main valleys at *discordant* levels.

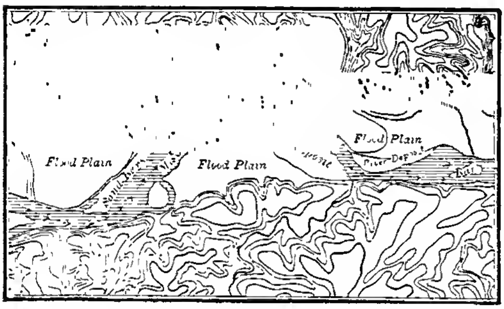



FIG. 90. Sketch map showing an early stage of the meandering of a stream. (From Tarr's "New Physical Geography," by permission of the Macmillan Company.)

**Stages of Valley History.** When any new land surface of at least moderate altitude is subject to erosion by streams, the valleys which develop pass through stages of youth, maturity, and old age. These stages show certain characteristics by which they can be recognized.

A *young valley* is narrow and steep-sided because down-cutting has thus far greatly predominated over processes of valley widening (Fig. 99). Tributaries are few in number, short, and not well developed. Streams on highlands which are new soon carve out deep valleys with V-shaped cross-sections. Although on newly exposed low lands with gentle slopes the young valleys are of course shallow, they are, nevertheless, narrow and steep-sided.

A *mature valley* is wider, less steep-sided, and usually deeper than a young valley (Fig. 99). It generally has numerous, relatively large, well-developed tributaries. Well along in maturity a flat begins to develop in the bottom of the valley because the stream in it is approaching grade, which means a steady diminution of down-cutting power, and an increase in its work of lateral erosion.

An *old valley* shows gently sloping sides, moderate to shallow depth,

and fewer tributaries than a mature valley (Fig. 99). A wide, nearly level floor (flood plain) also characterizes an old valley because down-cutting by its stream has practically ceased, and lateral erosion has developed the broad flats over which the stream flows in a sweeping, meandering course.

## Deposition by Streams

**Why Streams Deposit.** It should not be assumed from the preceding discussions that streams are everywhere constantly engaged in cutting down their channels, and so deepening their valleys. Some of the

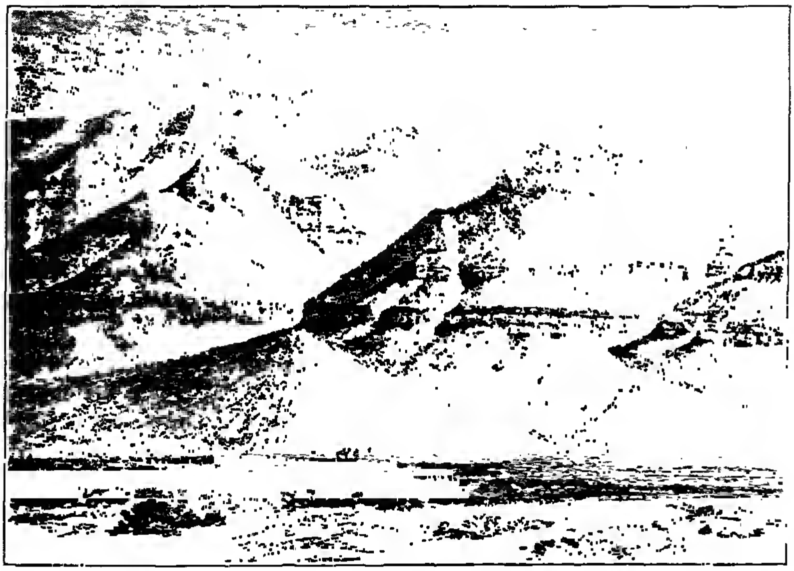


Fig. 91. Alluvial cones at mouths of canyons in southern Utah. (After U. S. Geological Survey.)

stream load may be temporarily dropped, while some or all of it may be permanently deposited.

The principal cause of stream deposition is diminution of velocity. It is a law of running water that a partial or complete checking of the velocity of a stream loaded with sediment causes deposition of a part or all of its load. Loss of velocity of a stream may be brought about (1) by decrease of slope of the stream bed, especially in the lower parts of a large valley; (2) by a decrease in volume, which always

means reduced velocity, as when a stream flows through an arid region where loss by rapid evaporation and sinking into the ground is not counterbalanced by new supplies from springs and tributaries; (3) by a change in the shape of the channel, as when a stream enters a wide, crooked channel just after emerging from a relatively straight, narrow channel; (4) by encountering any obstacle such as a boulder or stranded log in a relatively sluggish stream when a sand-bar or even an island may begin to develop; (5) by entering a body of standing water when the current is completely checked, and the whole burden of sediment is dropped. Deposition also takes place where a swift tributary carries

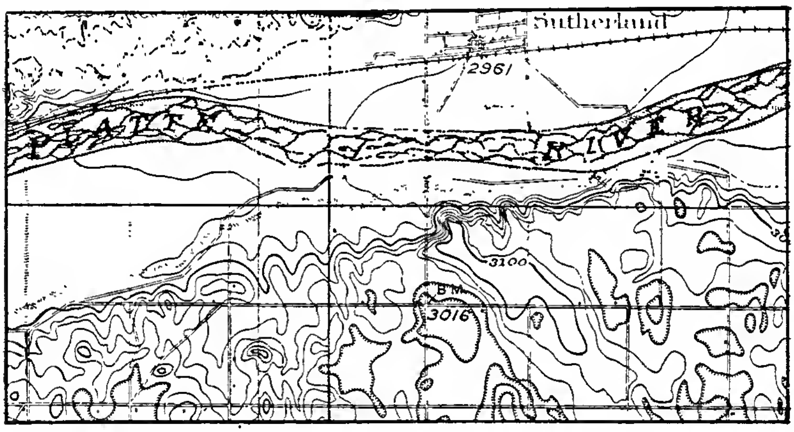



FIG. 92. A braided stream. Each square represents a square mile. South Platte River, Sutherland, Nebraska. (After U. S. Geological Survey.)

more sediment into a slow-moving larger stream than the latter can carry.

**Alluvial Cones and Fans.** When a swift, sediment-laden stream emerges at the base of a steep slope from a gully, gorge, canyon, or even ordinary valley upon a more nearly level lowland, there is a tendency for the load to deposit at and near the base of the slope. This is mainly because the velocity of the swift stream is suddenly checked. Such an accumulation of rock débris is generally in the shape of a partial cone. It is called an *alluvial cone* when it is steep, and an *alluvial fan* when its angle of slope is relatively low. Cones and fans vary in width from a few feet to a good many miles, and in thickness from a few feet to

many hundreds of feet. They are grandly displayed in the drier portions of the United States at the bases of mountains, as for example in Utah (Fig. 91), Nevada, and southern California.

**Stream-bed Deposits.** The current of an ordinary stream is so irregular that while, at a given time, much sediment is being moved downstream, some may be deposited in the back water of eddies, or in portions of the channel where the current is less rapid.

A stream which is carrying a load of sediment during a flooded condition must, as the flood declines, deposit part of its load in the channel because of loss of volume and velocity. Stream-bed deposits formed in the various ways just mentioned are, however, usually only temporary and of very local extent.

Stream-bed deposits assume much greater importance in the cases of streams which, on the average, tend to be overloaded and so are forced to deposit much of their sediment. Such streams build up (aggrade) their beds.

A stream like the Platte River is an excellent example of a *braided stream*, that is, one which does not flow in a single definite channel, but rather in a network of ever changing, branching, and reuniting channels (Fig. 92). The local portions of the stream flowing in such channels are called *distributaries*. They are easily explained as follows: When sediment is deposited on the bed of a channel the latter becomes too small to hold all the water, part of which then breaks over the side and flows in a new course. When the new channel becomes sufficiently clogged it in turn develops branches. By many repetitions of such a process and the frequent reuniting of channels, the network of courses of a braided stream is produced. The braided course does not exist as such during high water because then the whole flat, which during lower water contains the network of channels, is covered by the stream.

Gravel or sand bars form in some streams which do not become braided. These are most likely to develop at times of low water. A given bar may be partly or wholly cut away by high water (with increased velocity), or it may last for some time as a low-water island.

**Meander Deposits.** When a stream reaches a graded, or approximately graded, condition, and develops meanders, it does so by a twofold process of cut-and-fill. While the current which is directed against the bank of the outer portion of a meander is there performing the work

of lateral cutting or erosion, the current is relatively slack on the side of the channel directly opposite, and so deposition takes place there up to flood level. On the side where cutting takes place, the bank is steep and the water deepest, while on the opposite (filling) side the bank slopes gently, and the water is shallowest. If it were not for this twofold process of filling on one side of the channel, and cutting into the opposite bank, the meander could not long continue to develop because cutting alone would widen the channel to such an extent that the greatly weakened current would lose its power of lateral erosion (Fig. 90).

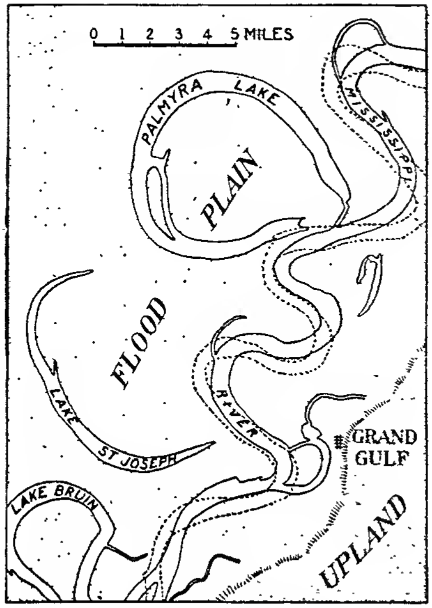



FIG. 93. Meanders and oxbow lakes of part of Mississippi River flood plain in 1883 (heavy lines) and 1896 (dotted lines). (By William Davis, based upon Government Surveys.)

**Flood-plain Deposits.** In most cases by far, flats on valley bottoms are developed by the lateral erosion of streams, particularly when they are graded or nearly so. This process has already been explained. In some cases valley-bottom flats are formed by aggradation, as is the case when any land area with its valley subsides so much that enough deposition of sediment must take place in the valley to build up its floor to a graded condition. However they are formed, valley flats subject to overflow during high water are called *flood plains*, as already defined.

When a typical flood plain is covered by high water the current following the main (low water) channel has its velocity greatly augmented so that not only is its power to transport increased, but also it then actually erodes (cuts down) its channel. In the meantime the sediment-laden water over the flood plain has a velocity much less than that of the main current so that some deposition takes place there (Fig. 94).

When muddy water covers the flood plain of a river, the conditions

for deposition are most favorable along the edges of the main channel because there the sediment-laden current of the swift-moving channel water is suddenly greatly checked by friction against the slower moving waters of the flood plain. Because of this sudden diminution of carrying

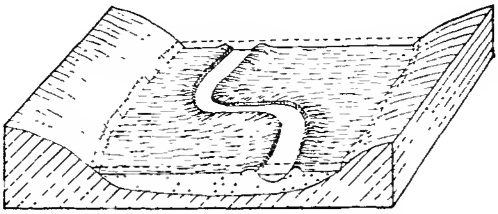


FIG. 94. Diagram illustrating river flood plain, deposits, and natural levees. Dotted line shows high-water level.

power along the edges of the main channel, more and coarser materials deposit there than over the general flood-plain surface. Low ridges of such origin are called *natural levees* (Fig. 94).

## DELTAS

**Cause of Deltas.** Much sediment carried by a stream finally reaches its mouth. If the stream flows into a lake or the ocean, the velocity of the current is largely or wholly checked, and thus much or all of the sediment must be deposited. The destination of most streams is the sea, and, where tides or shore currents in the sea are relatively weak, the discharged sediments accumulate mainly at and near the mouths of the streams in the form of flat, partly submerged, fan-shaped deposits called *deltas*. The name has been given because of the crudely triangular shape similar to the fourth letter of the Greek alphabet. If there are strong tides or shore currents in the body of water which the stream enters, or if the amount of sediment discharged by the stream is relatively small, the tendency is either for the sediment to be swept so far away from the mouth of the stream that no delta will form, or only a small or imperfect one will develop. Another reason for the absence of deltas from the mouths of many existing rivers (even some large ones) is the sinking of the land, causing notable submergence of the mouths of the rivers so recently that there has not been time enough for the discharged sediments to build up real delta deposits around the newly located mouths.

**Examples of Deltas.** Some examples illustrative of the principles just explained will now be given. Very large and typical deltas have been, and are being, formed where big rivers empty into certain lakes or nearly enclosed arms of the sea. Thus the great Nile River has built into the Mediterranean Sea a very typical delta covering about 10,000 square miles (Fig. 95). The Mississippi River has extended its delta of 12,000 square miles some 200 miles into the Gulf of Mexico. Extensive deltas have been built by the Danube River into the Black Sea, and by the Volga River into the Caspian Sea. In the face of considerable tidal action, the Hwang-ho River of China has built into the Yellow Sea a vast delta of fully 100,000 square miles.

**The Delta Surface.** What are some of the characteristic features of the common type of delta? Its surface is a wide, nearly flat, usually fan-shaped plain mostly a little above, and partly a little below, the level of the body of water into which it grows. Thus about two-thirds of the surface of the Mississippi delta is above water under ordinary conditions, but most of it is inundated by high water during a flood. The great bulk of delta material is, however, always under water, and thus it differs from an alluvial cone or fan whose material is wholly, or largely, on land. Another almost universal feature of a delta surface is the presence of *distributaries,* that is, branches into which the stream splits in increasing number, beginning at the head (upper end) of the delta. These distributaries wander over the delta plain in an ever widening network, and so a delta-forming river always has several or many mouths (Fig. 95).

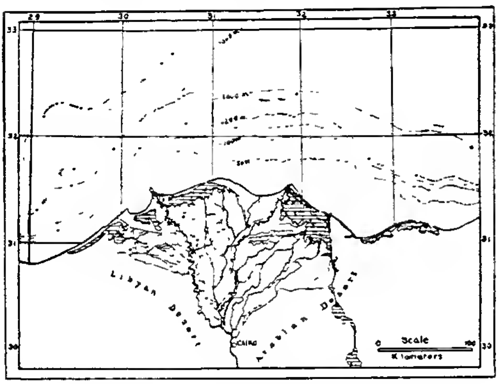


FIG. 95. Delta of the Nile. Depth of water in meters. (After J. Barrell.)

**Delta Structure.** The delta shows a characteristic structure because of the special conditions under which deposition of the sediment takes place. Thus the steep front (Fig. 96), so characteristic of a delta, results from rapid deposition of the coarser sediment layer upon layer where the onrushing sediment-laden stream (or each mouth of the

stream) meets the relatively deeper standing water into which the stream flows. These steeply inclined layers are called *fore-set beds* (Fig. 96). They make up the greater bulk of the delta pile. The finer sediments spread out in layers over the floor of the lake or sea to a greater or less distance out from the base of the steep front of the delta. These layers are called the *bottom-set beds.* The earlier formed bottom-set beds of course become buried under the fore-set beds. The *top-set beds* are deposited by the stream on top of the fore-set beds as the latter advance into sea or lake and shoal the water. They build up, for the most part, to a little above the level of sea or lake in layers which slope very greatly seaward or lakeward.

**Rate of Growth of Deltas.** Some rather accurate data regarding the rate of growth of various deltas are known. A few examples will be mentioned. One mouth of the Mississippi River is growing into the

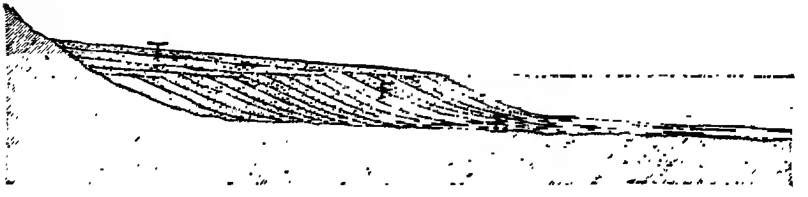



FIG. 96. Ideal structure section of a delta. T = top-set beds; B = bottom-set beds; F = fore-set beds. (Modified after G. K. Gilbert.)

Gulf of Mexico at the phenomenal rate of one mile in 16 years. The River Po has extended its delta 14 miles into the Adriatic Sea in 1800 years as proved by the fact that Adria, a seaport at the mouth of the river, 1800 years ago, is now 14 miles inland. The Rhone River has been building its delta into the Mediterranean Sea at the rate of one mile in 100 years for many centuries. The ancient seaport of Rome is now three miles inland because of delta extension by the Tiber River. But by no means do all deltas build out so fast. Thus the great delta of the Nile has grown seaward but little in 2000 years because a current sweeping along the delta front is strong enough to keep the sediment removed about as fast as it is supplied by the river. The Amazon River has not been able to build a delta deposit even up to sea level because of the very strong tides and sea waves, though it has constructed an extensive submarine delta covered by water less than 60 feet deep.

## History of Stream Courses

**Consequent Streams.** On any new land surface, the first streams will have their courses determined by the original slope and natural irregularities of the surface. Such stream courses are, therefore, consequent upon the original relief features. They may of course not only lengthen by headward erosion, and deepen and widen their valleys, but they may also have tributaries developed as a direct consequence of the initial topography. All such streams whose courses are the direct consequence of the initial topography are called *consequent streams.*

**Subsequent Streams.** During the history of a drainage system, it happens almost invariably that many stream courses originate independently of the original (initial) topography, and are determined and regulated by erosion proceeding differently upon the bed rock formations according to differences in hardness, structure, and resistance to erosion of the formations. Such streams are said to be *adjusted* because they carve out their valleys along lines or belts of the weaker or more yielding rocks.

All streams which develop independently of, and subsequent to, the original relief of a land area, whether by adjustment to rock character or structure, shifting of divides, stream capture, or any other process, are called *subsequent streams* in distinction from consequent streams. Subsequent streams are very commonly tributaries of consequent streams, but even a consequent stream course may, during the progress of erosion of a region, undergo sufficient change to become subsequent.

**Normal Cycle of Erosion.** By a *normal cycle of erosion* we mean the time required for the reduction to or near base level by erosion (mainly stream action) of a new land area of at least moderate altitude with a humid climate, and with no interfering change of level of the land by earth-crust movements. The principles involved may be best set forth by tracing through the stages in the topographic development of a land mass under the conditions just described, and with an initial sloping surface reaching to hundreds or even thousands of feet above sea level. Beyond in this chapter, some of the more important variations and interferences with the so-called normal cycle are discussed.

*Infancy stage.* A typical newly formed land surface, like the kind just pictured, has a drainage system developed upon it. In the earliest stage (infancy) of its cycle of erosion, only a few streams form, and these tend to seek out the original depressions, and to flow down the

initial slope of the land. These are, of course, consequent streams. From the very start some of these streams will be longer, larger in volume, and more energetic as erosive agents than others. A characteristic of all is the small number of tributaries. Not uncommonly some original basin-like irregularities, or depressions, will be filled with water to form ponds or lakes. During infancy, stream erosion accomplishes very little, but the process of sheet erosion is then most effective.

*Youthful stage.* The region relatively soon passes into the next

FIG. 97. An aerial view of gully development illustrating an early stage of topographic youth. Kettleman Hills, California. (© Spence Air Photos.)

stage called *youth* (Fig. 99). During this stage the streams carve out narrow, very steep-sided valleys usually with V-shaped cross-sections (Fig. 98). All of the streams are very actively engaged in deepening their valleys by erosion, or in other words, none of them have reached a graded condition. Flood plains and meandering streams are therefore lacking. During this youthful stage, there are few if any sharp divides (divisions of drainage), and the streams are still relatively few in number. The relief of the region is, for most part, not rough. Gen-

eral erosion of the region is not far advanced because erosion is largely confined to the relatively few stream channels. Gorges (or canyons), waterfalls, or lakes (or ponds) are not uncommonly present because they are geologically short-lived features which are indicators either of a youthful topographic stage of a region, or of some geologic process or disturbance which has recently affected a topographically older region, as pointed out beyond. Some examples of regions in topographic youth are much of the Atlantic Coastal Plain of the United States which

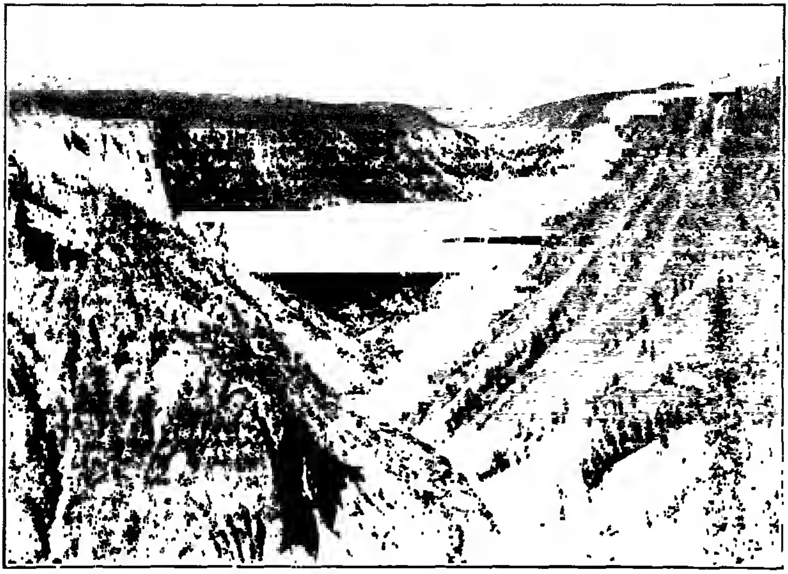


FIG. 98. A youthful V-shaped valley cut in a high plateau of lava. Grand Canyon of the Yellowstone, Yellowstone Park. (After W. T. Lee, U. S. Geological Survey.)

has recently emerged from the sea; the Colorado Plateau of Arizona, with its Grand Canyon, which has been upraised in recent geologic time to its present altitude; and the general vicinity of Fargo, North Dakota, which is part of a large lake bed from which the water has been so recently drained that it is in early youth.

*Mature stage.* Erosion continues until the features so characteristic of youthful topography gradually give way to those distinctive of *maturity* (Fig. 99). A region in typical maturity has the maximum number (usually a network) of streams most of which flow in valleys which

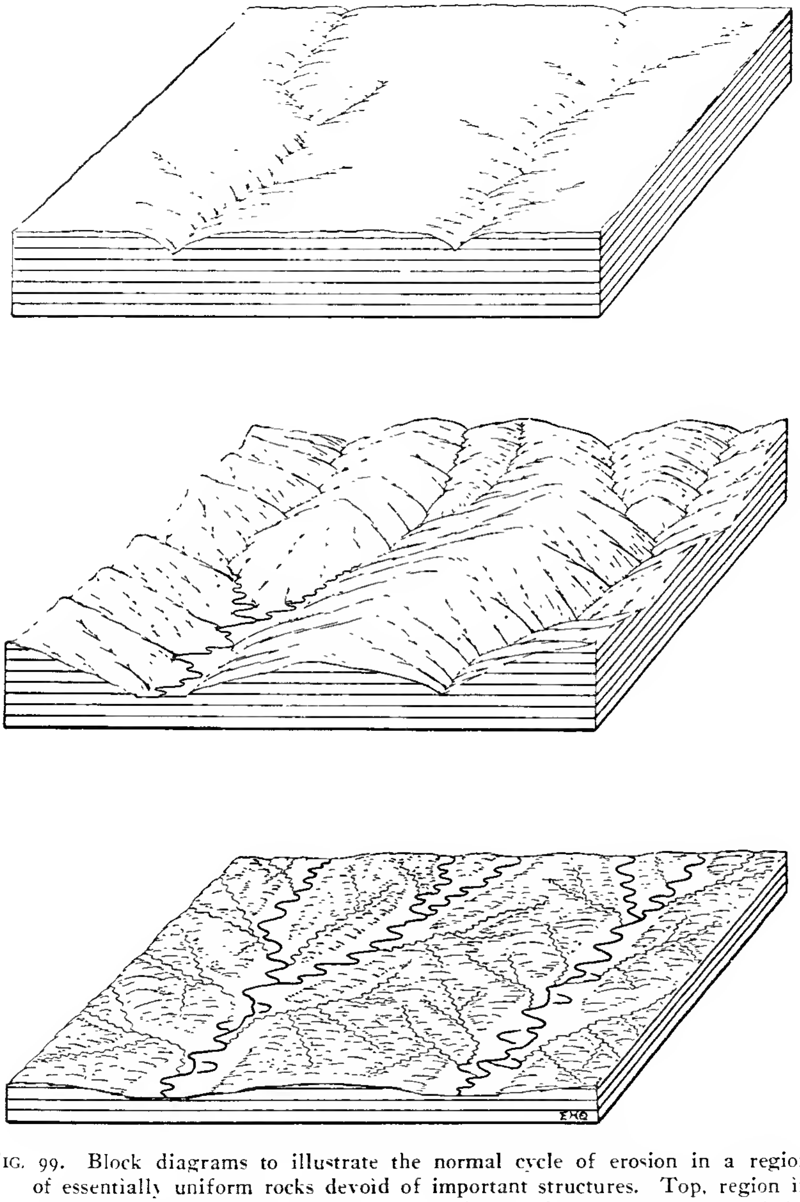


FIG. 99. Block diagrams to illustrate the normal cycle of erosion in a region of essentially uniform rocks devoid of important structures. Top, region in youth; middle, in maturity; bottom, in old age. See text for characteristics of stages.

are wider and less steep-sided than those of youth, that is, their cross-sections are broader V-shaped. The maximum roughness of relief has developed. Divisions of drainage (divides) are well-defined and sharp. General erosion is, in fact, then most effective because practically the whole region has been cut to steep slopes. Waterfalls, gorges (or canyons), or lakes (or ponds) rarely if ever exist because time enough has been given for the streams to obliterate such temporary features. Between middle and later maturity one (or more) of the larger streams of the region has cut down near enough to a graded condition (at least in its lower course) to begin meandering with resultant development of a flood plain. During maturity a river system does its maximum work in regard to amount of down-cutting, quantity of water carried off, and load of sediment transported. A very fine illustration of a region in typical maturity is that around Charleston, West Virginia. A wide region around Lancaster in southwestern Wisconsin, including a part of the Mississippi River, is also a good example of maturity. Except for the very recent addition to it here and there of some minor features of youth, as inheritances of the Ice Age, such as gorges, waterfalls, and ponds, the region of central-western Massachusetts, with its Connecticut Valley, is a fine example of a region in late maturity (Fig. 100).

*Old-age stage.* As the erosion of the region progresses, the *old-age* stage (Fig. 99) is reached when the relief has been greatly subdued to the condition of an undulating plain, or so-called "rolling country." Divides are then not at all sharp, being low, rounded hills. Only a moderate number of streams remain, and these flow through wide, shallow valleys. Most of the streams (especially the larger ones) are graded or nearly so, and their sweeping meanders and cut-off meanders (oxbows) on wide flood plains are common and characteristic. General erosion and the amount of work accomplished by the streams are much less than in maturity. Gorges and waterfalls are absent, but oxbow lakes, which are easily distinguished as such, are present. A region well along in the old-age stage of its erosional history has a highly subdued topography of very low relief, which, in the final stage of a perfect cycle of erosion, would be a featureless plain at base level. It is doubtful if any wide area has ever been reduced to such a base-leveled condition, although such a condition has often been rather closely approached. Very typical examples of old-age topography are south-

central Kansas in the general vicinity of Caldwell, and the region around Butler, Missouri.

*Time involved.* The terms infancy, youth, maturity, and old age, as above employed, do not denote anything like definite periods of years, but rather they represent stages, each with certain characteristics, of the cycle of erosion of any given region. Since conditions of altitude, slope, rock character, and rainfall of different regions vary so widely, it is clear that either topographic maturity or old age may, as measured in years, be reached in one region, or even a portion of a single region, long before it is in another. The terms under consideration "have reference not so much to the length of their history in years as to the amount of work which streams have accomplished in comparison with what they have before them."

FIG. 100. A region in maturity. Connecticut Valley of Massachusetts. (Howell's relief model.)

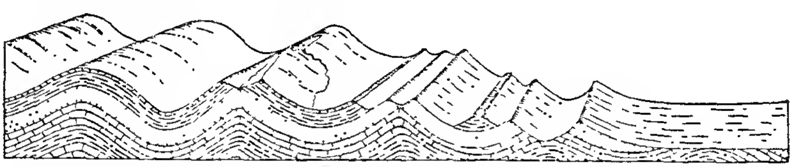



FIG. 101. Diagram to illustrate successive stages in the normal cycle of erosion in a region of folded rocks. (After G. H. Ashley.)

**Peneplains and Monadnocks.** *Definitions.* Any region which has been worn down by erosive agencies to a condition of very low relief at, or nearly at, base level is called a *peneplain* (or peneplane), meaning an "almost-plain." A perfect peneplain would be a plain wholly at base-level-of-erosion, but because probably no large land area has ever been completely base-leveled, it is customary to call a region of faint

relief, well along in the old-age stage of its erosion, a peneplain. Perfect base-leveling of a region must rarely if ever take place because, as old age is approached, the rate of erosion becomes slower and slower as

FIG. 102. Block diagram showing a peneplain surmounted by a monadnock of more resistant rock. (After W. M. Davis.)

the gradients of the streams become less and less, so that the time necessary for perfect planation would be almost infinite. Almost invariably diastrophism, igneous activity, glaciation, or some other process notably affects the region long before anything like a perfect peneplain, or base-leveled condition, is reached.

It often happens that, during the development of old-age (or peneplain) topography, more or less local portions of the region are not cut down to the general peneplain level, either because they consist of more resistant rocks, or because they lie in the midst of relatively wide spaces between larger streams, and so are more favorably situated against erosion. Such a residual mass rising well above the general peneplain level is called a *monadnock*, so named after Mount Monadnock of New Hampshire which rises conspicuously above the now upraised, and partly eroded, peneplain of southern New England.

*Existing peneplains.* Peneplains, or even reasonably close approximations to them, are not very common over wide areas of North America, as may be inferred from the above discussions. One reason for this is the fact that so many portions of the continent, including many well-worn-down (practically peneplaned) areas, have been more or less uplifted in recent geologic time (Cenozoic era), and subjected to renewed erosion. Much of the large area comprising central-western Missouri, southeastern Kansas, and northeastern Oklahoma has been reduced by erosion to a condition of old-age topography approaching a peneplain though still lying hundreds of feet above sea level.

*Recently upraised peneplains.* The vast eastern Canadian region extending from near the international boundary northward to either side of Hudson Bay, consists of a complex mixture of very old rocks and structures which, after long ages of geologic time, was mostly reduced to a common level of very low altitude. This so-called "Laurentian Peneplain" has since (in the Cenozoic era) been rather unevenly

upraised in amounts varying from a few hundred feet to about 2000 feet. In the interior of Labrador, for example, the old, eroded, upraised, peneplain surface is so smooth that variations of level are only a few hundred feet within an area of 200,000 square miles.

It has long been known that most of the eastern United States, where the higher lands such as southern New England, New York, and the northern and central Appalachians are situated, was, during later Mesozoic time, subjected to such widespread and deep erosion that it was all worn down to the condition of a remarkably smooth plain (peneplain) near sea level with slow-moving (graded) streams meandering over its surface. The differential uplift of this vast peneplain to altitudes up to a few thousand feet took place in the present (Cenozoic)

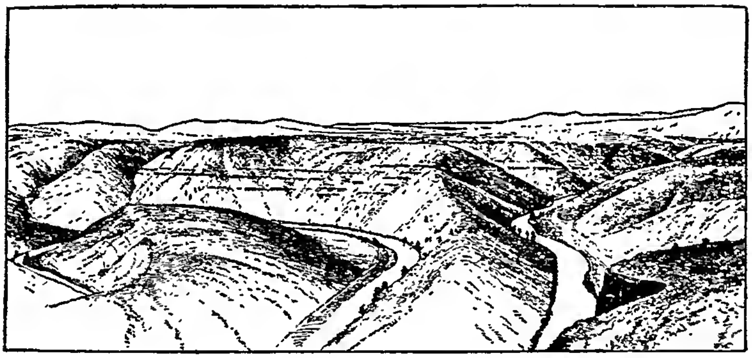


FIG. 103. A rejuvenated region showing entrenched meanders. Yakima Canyon, Washington. (Hobbs, after G. O. Smith.)

era of geologic time during which the present-day ridges and valleys of the Appalachian Mountains have been produced by erosion.

**Interrupted Cycles of Erosion.** *Rejuvenation.* The normal cycle of erosion, which, as we have shown, ends with a peneplain condition, may be interrupted at any stage by other processes. Such processes are so varied, and their effects are often so complicated, that we shall attempt only to explain briefly some of the more important ones and their general effects.

The most common and significant cause of interruption of the normal cycle of erosion is change of level of the land (diastrophism). Thus a region in any stage of its erosional history prior to almost complete peneplanation, say in maturity or early old age, may be upraised with resultant notable increase in velocities of the streams. Such a region is said to be *rejuvenated,* and the streams whose activities are quickened

are said to be *revived*. The revived streams begin to cut youthful valleys in the bottoms of the wider, older valleys, and thus a new cycle of erosion is inaugurated. The effect is at first most pronounced on the valley floors of the streams which are graded, or nearly so, but in time the whole region is distinctly affected by the revival of erosive activity.

If, through processes of erosion, a meandering stream develops on a flat valley-bottom, and then uplift of the land takes place, the revived stream proceeds to cut a youthful valley in the old valley floor without changing its meandering course. Such meanders are known as *en*

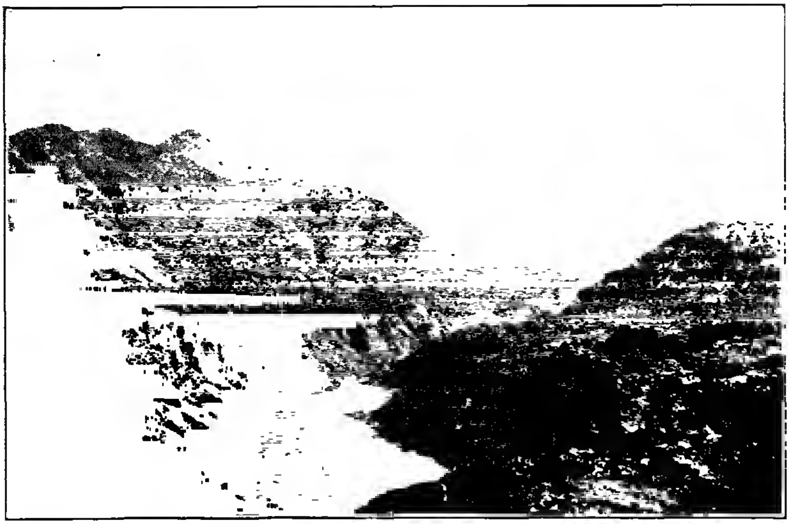


FIG. 104. A rejuvenated region showing a youthful valley cut into an older, mature valley. Matanuska Valley, near Glacier Point, Alaska. (Photo by Mendenhall, U. S. Geological Survey.)

*trenched* (*or incised*) meanders. Among numerous excellent examples are the San Juan River of southeastern Utah, Yakima Canyon in Washington (Fig. 103), the Susquehanna River of southern New York and northern Pennsylvania, and certain rivers of western Germany, Belgium, and northwestern France.

In a case of uplift of a region which has undergone practically complete peneplanation, or base leveling, the general effect is, in nearly all respects, like a new land surface (with consequent streams) formed in other ways, and it may be treated as such. Such a case scarcely comes under the category of an interrupted cycle of erosion.

Rejuvenation may be by uniform uplift, tilting, warping, folding, or faulting of a land surface in any stage of erosion. An excellent example involving uplift and tilting of a great fault block is that of the Sierra Nevada Range (Fig. 105).

*Cycle interrupted by subsidence.* Subsidence of the land also interferes with a normal cycle of erosion. Its general effect is to hasten old age by diminishing the amount of erosive work the streams have to do. Continued sinking causes deposition of sediment in the valleys (or portions of them), thus building up their floors.

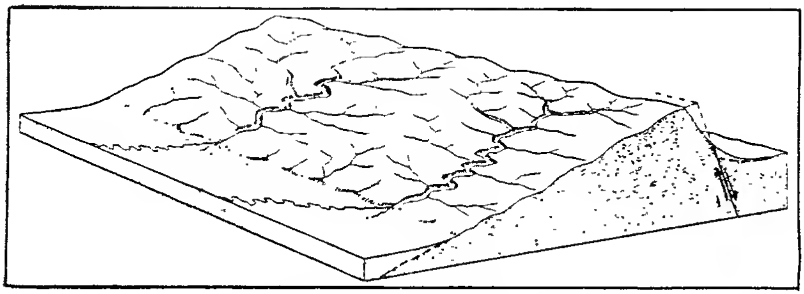


FIG. 105. Diagram representing a portion of the great Sierra Nevada fault-block geologically recently rejuvenated by faulting. (After Matthes, U. S. Geological Survey.)

If a seaboard region in any stage of erosion, particularly from typical youth to typical old age, subsides enough relative to sea level, tidewater floods at least the lower courses of the valleys and their streams, and they are said to be *drowned.* Not only are such valleys, or parts of them, drowned, but also the general erosion of the remaining land is diminished. Such a drowned valley becomes an *estuary,* while the former tributaries of the main stream, now forced to enter tidewater by separate courses, are said to be *dismembered.* The recently sunken coast of Maine is a fine illustration of many drowned-river valleys. The drowned valley of the lower Susquehanna River (Chesapeake Bay), and of the lower Hudson River, are also good examples of such estuaries. The submerged valley of the Hudson has been definitely traced across the sea bottom for fully 100 miles out from New York City (Fig. 6).

*Other causes of interrupted cycle.* It should not be presumed, from the foregoing statements, that interruptions of the normal cycle of erosion are brought about only by changes of level of the land. Thus the whole northeastern portion of the United States from Minnesota and Iowa to the New England coast was in a topographic condition varying

from maturity to early old age just before the great Ice Age. Then, during and after the recession of the great sheet of ice from the region, extensive deposits of glacial and post-glacial rock débris were left more or less irregularly strewn over much of the surface, giving rise to many low hills, lake basins, and altered drainage courses which latter have not uncommonly developed gorges and waterfalls. Thus many distinct features of a youthful topography are, as a result of glacia-

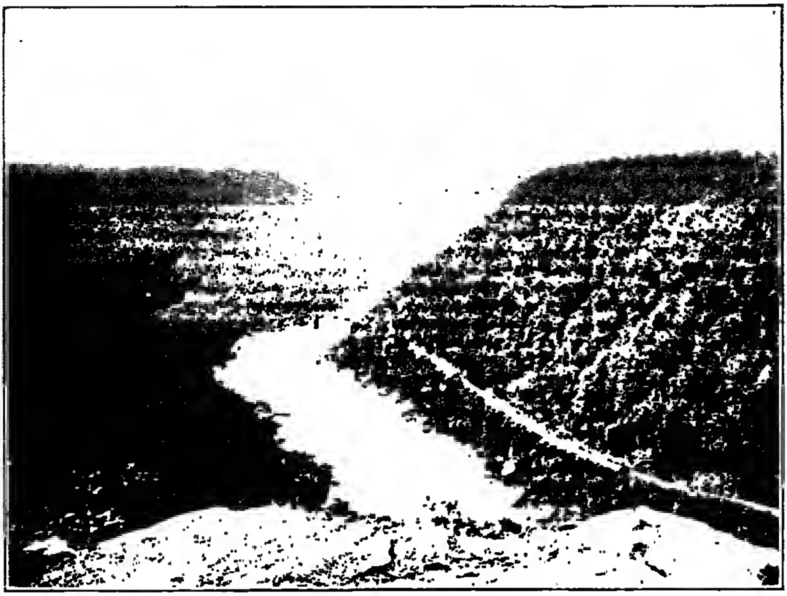


FIG. 106. A valley being cut in the uplifted Appalachian peneplain. Note the even sky line of the mountains. New River, Virginia. (After Hillers, U. S. Geological Survey.)

tion, superimposed upon a large land area which was otherwise well along in its erosional history.

Extensive outpourings of lava may profoundly interrupt the normal cycle of erosion of a region as is so well exemplified on a grand scale in the Columbia Plateau stretching from the Yellowstone Park region westward across Idaho and into eastern Oregon and Washington. The old erosion surface with its stream systems was almost completely buried under the thick accumulations of lava, and new stream courses have been established upon the newer surface of the lava fields.

**Desert Cycle of Erosion.** *Streams of arid regions.* The cycle of erosion under arid climate conditions shows certain characteristic dif-

ferences from the normal cycle in humid regions. Rainfall and, therefore, vegetation, are scant. An arid-climate characteristic is that the rain which does fall is likely to be concentrated in a few downpours, each of very short duration, in the course of a year, or possibly several years. Large trunk streams seldom if ever develop. A few only of the stronger streams flow the year round, and most of their tributaries contain water only during, and shortly after, the rare periods of rain.

*Stages of a typical desert cycle.* The arid cycle of erosion is so much influenced by the nature of the original topography of the region that the order of events in a cycle varies considerably. Our present purpose is to discuss only the more general principles as they would be illustrated in a rather typical arid region of varied topography with block mountains and intermont basins, with no stream outlet to the sea, and undisturbed by changes of level of the land during the cycle.

A great, typical, desert basin like that just described has, in *infancy* of topographic development, consequent drainage courses established upon the initial surfaces, including the mountain slopes. These streams, which are seldom active except during and after heavy rains, do not become tributary to a perennial trunk river draining the whole great basin or a large part of it, but they flow down upon the floors of the various local basins where they mostly sink away, or evaporate, or in a few cases enter permanent or temporary ("playa") lakes. Most of the streams are, therefore, mere fragments of what, under humid climate conditions, would be a river system with its trunk river and numerous tributaries.

"In the *youth* of the cycle the highlands are slowly eroded, and deposition takes place on the slopes and floor of each basin, diminishing the relief and raising the local base level, a strong contrast to the corresponding stage of the normal cycle in which relief is increased by the excavation of stream valleys. Even in arid regions, however, valleys are cut on the highland slopes, while the basin floor is made nearly level by deposition (Fig. 107). This stage is exemplified by the Great Basin and its mountains. Water is the chief agent of erosion and deposition during the period of youth, but the wind is also important in eroding the bare rocks, and in distributing the finer waste, part of which it carries outside of the arid region altogether. Extremely slow as this process of complete removal of the finer débris by the wind undoubtedly is, yet it is the only agency which actually lowers the average altitude of the region, for no water flows out of the area we are considering" (W. B. Scott).

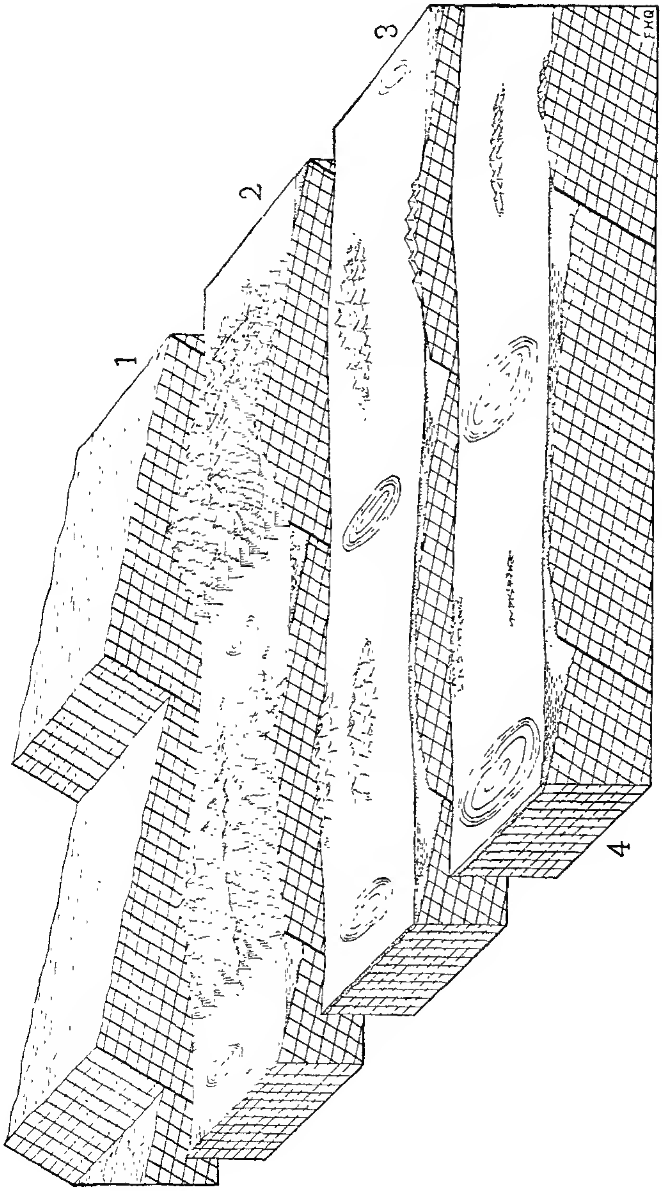



FIG. 107. Block diagrams illustrating a desert cycle of erosion. 1, represents fault-block mountains as they would appear if unaffected by erosion; 2, youthful stage; 3, mature stage; and 4, old age stage. Important features are explained in the text. Cross-lines indicate bed rock; stippled portions, sediments; and parallel-lined areas, playas.

*Maturity* of the region is reached when the highlands are deeply eroded, and enough of the resulting sediments have been carried down and deposited on the floors of the original separate basins to cause them to coalesce. "As the coalescence of basins and the integration of stream systems progress, the changes of the local base levels will be fewer and slower, and the obliteration of the uplands, the development of graded piedmont slopes, and the aggradation of the chief basins will be more and more extensive" (W. M. Davis). During maturity the

FIG. 108. A view across a deep desert basin showing how it is being filled with sediment (so-called "wash") carried down from adjacent mountains on each side. The floor of the basin, 6 miles wide, is below sea level. The range across the basin is more than a mile high. Note the fine large alluvial fan at its base. Looking west about 5 miles north of Furnace Creek Ranch, Death Valley, California.

erosive action of the wind becomes relatively more important not only because rainfall is less on the lowered highlands, but also because the swiftness, and hence erosive power, of the streams are much reduced on account of the lower relief (Fig. 107).

As *old age* is approached the original highlands are cut down lower and lower, and the now coalesced, local basins are built up more and more until the whole region becomes a wide, nearly flat expanse with broad, gentle undulations consisting of bare-rock plains (truncated

highlands) merging into plains of deposition (filled basins). Such a combination plain may be far above sea level. Here and there masses of more resistant rocks may stand out as residual masses corresponding to monadnocks of the normal cycle of erosion (Fig. 107). During late old age in a very dry region the wind is the only very active agent of erosion. By its corrasive power the wind tends to erode hollows and irregular depressions in the weaker rocks. The wind also transports some sediment past the confines of the arid region, this latter process being of course the only one by which the general level of the old-age plain is reduced.

**Stream Capture.** *General principles.* During the erosional history of a region it often happens that certain streams steal parts (or all) of other streams by a process known as *stream capture* or *piracy*. The general principle involved is that a stream which finds various conditions for valley development (erosion) more favorable than a near by stream may, by headward extension of itself or one of its branches, tap and divert into itself part (or all) of the stream whose erosional conditions are less favorable. A stream whose upper waters have been captured is said to be *beheaded*. Through the process of stream capture there is a strong tendency for many streams to leave the harder, or more resistant rocks, and develop courses in softer, or less resistant, rocks, that is, they tend to adjust their courses to the character and structure of the various rock formations of a region. This is known as *structural adjustment* of streams.

*Examples of stream capture.* Some of the more common principles of stream capture may be made clear by explanation of a few definite cases. Thus, two streams flowing roughly parallel to one another may each develop a tributary reaching out toward the other as shown by Figure 109. Because one of these streams is more active, and has cut its valley deeper, its tributary also cuts down faster, and works headward faster, than the tributary of the other stream. The head of the more active tributary finally reaches the less active tributary and carries off its upper waters. This is a common method of stream capture in many regions.

Where two streams follow approximately parallel courses (one higher than the other) lateral erosion of one or both may at some place completely remove the divide which separates them, causing the stream at the higher level to drain into the lower-level one.

The capture of the upper part of Beaverdam Creek by the Shenandoah River of Virginia is a well-known case of stream piracy. As

shown by Figure 110, the Shenandoah developed as a tributary of the Potomac in an early stage of the erosion of the newly uplifted region. Both the Potomac River and Beaverdam Creek cut gorges through the hard rock of Blue Ridge, but the former deepened its valley much faster. The young Shenandoah was, therefore, enabled to extend its course southward by headward erosion, and finally tapped, and diverted into itself, the upper part of the higher level Beaverdam Creek. The abandoned channel of the creek across the Blue Ridge is still plainly preserved.

The short, swift rivers which flow down the western side of the Andes Mountains of Chile have captured the source streams of many

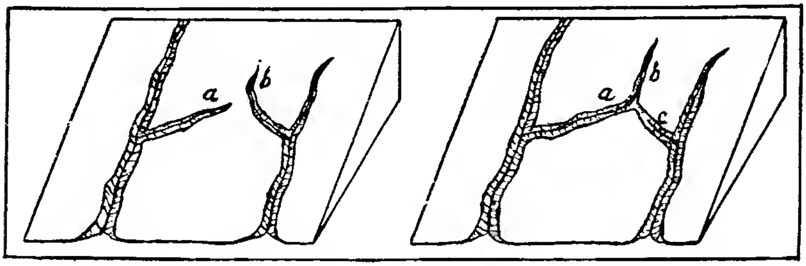



FIG. 109. Diagrams illustrating a simple case of stream capture by headward growth of a tributary. (Modified after Salisbury.)

of the longer, slower rivers which flow down the eastern side of the mountains and across Argentina.

**Antecedent Streams.** A type of river of special interest is one which during, and for a time at least after, disturbance (by diastrophism) of its drainage area maintains the course it had before the disturbance began. Such a stream is said to be *antecedent* because its course was established before the land across which it flows was disturbed by earth-crust movement. The simplest case is that of a revived river resulting from rejuvenation of a region by uplift without much change in the general direction of slope of the land. Thus the rivers of central and western New York have, as already explained, cut valleys in a rather uniformly upraised peneplain. Since such antecedent rivers merely renew down-cutting along their old courses, it is, perhaps just as well to call them simply revived rivers.

A remarkable type of antecedent river is one which has kept its course through a rising barrier, even a mountain range. Thus the Columbia River has maintained its course right across the slowly up-

warping Cascade Range by cutting a canyon several thousand feet deep while the uplift was in progress. If the uplift had gone on faster than the river could erode its channel, the river would have been diverted.

As the Wasatch Range of Utah slowly rose (in recent geologic time) across the path of the Ogden River, the river maintained its course by cutting a deep canyon.

The Indus and Brahmaputra Rivers of northern India are believed to be antecedent, for they cut great canyons through a main range of the Himalayas, and then flow into the Indian Ocean.

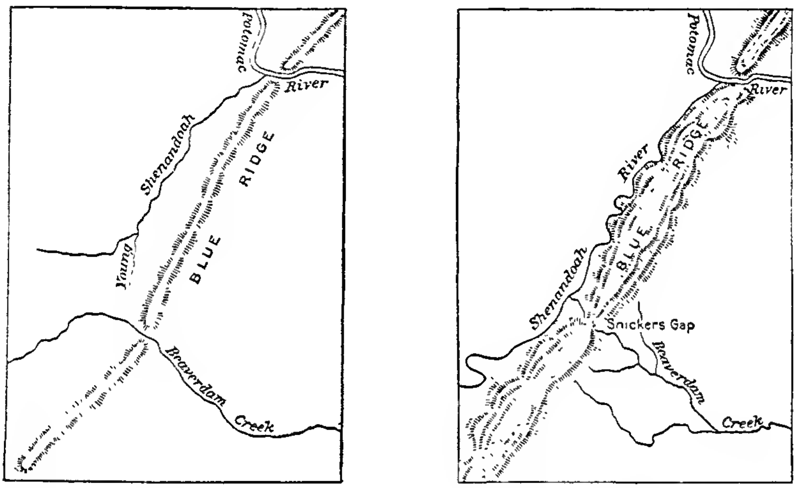



FIG. 110. Sketch maps showing how the upper waters of Beaverdam Creek were captured by the Shenandoah River. (After B. Willis, U. S. Geological Survey.)

**Superimposed Streams.** An old land mass with characteristic topography, rock character, and structure may be buried under later rock formations of very different kinds and arrangement. The newer, overlying accumulations may be sheets of lava, volcanic ash-beds, glacial deposits, lake deposits, or marine strata. The surface of the newer formation may be utterly different from that of the older, underlying formation.

A simple case to consider is a series of gently sloping, nearly smooth strata resting on top of a rugged surface of igneous and irregularly tilted metamorphic rocks. It not uncommonly happens that a stream, whose course has been determined upon the newer surface, cuts through the overlying rocks and into the underlying rocks, maintaining its course

irrespective of the surface, character, and structure of the underlying rocks. Such a stream is said to be *superimposed* or *inherited* (Fig. 111). A fine example is the Colorado River in the Grand Canyon of Arizona where the river has cut through a thickness of several thousand feet of nearly horizontal strata, and into a very ancient, worn-down, buried mountain area consisting of a complex arrangement of hard igneous and metamorphic rocks. In the strata the canyon is wide and ter-

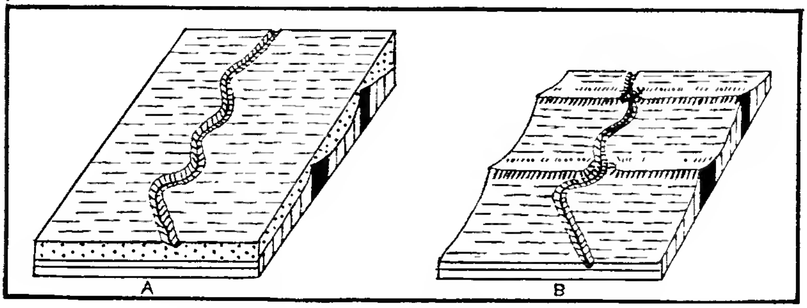



FIG. 111. Diagrams illustrating the development of a superimposed river.

raced, but in the hard, underlying rocks a deep, narrow, steep-walled gorge has been (and is being) cut by the river.

Where, through erosion, the overlying rock mantle has been completely removed from the underlying rocks of different structure, the superimposed streams may have courses very strikingly out of harmony with the structure of the formerly buried rocks. Thus in the Lake District of England a system of streams with a distinctly radial arrangement has been superimposed upon a once buried body of rocks with a northeast-southwest trend. This is a fine example of a superimposed, or *inherited drainage system.*

## Special Effects of Stream Work

**Canyons and Gorges.** *Definitions.* Deep, narrow, steep-walled valleys are called gorges (e.g. Niagara Gorge), chasms (e.g. Ausable Chasm of New York), dells (e.g. Dells of the Wisconsin), glens (e.g. Watkins Glen of New York), or canyons (e.g. the Grand Canyon of Arizona). The term canyon is generally applied to a large gorge or chasm.

*Factors favoring canyon development.* Factors particularly favorable to the development of canyons and gorges are rapid down-cutting by

streams, and rock formations hard or resistant enough to maintain steep slopes or cliffs when they are cut into. An arid climate is usually more favorable than a moist one because certain weathering agents which cause valley widening are less effective under dry climate conditions. In the development of a gorge or canyon the down-cutting (erosive) action of a stream proceeds so rapidly that the agents of valley widening do not have time to reduce notably the steepness of the valley sides.

*Zion Canyon.* A remarkable example of a deep, very narrow canyon is the northern portion (so-called "Narrows") of Zion Canyon, Utah, where a very swift, sediment-laden stream under semi-arid conditions has cut its way down into moderately hard rock (sandstone) so fast as to develop a gorge over 1500 feet deep, 20 to 40 feet wide at the bottom, and a few hundred feet (or less) wide across the top (Fig. 88). The main part of Zion Canyon, some 12 miles in length, varies from 2000 to nearly 4000 feet deep. It is bounded by precipitous walls of red, horizontal beds of massive sandstone overlain with light gray sandstone. The canyon gradually gets wider toward its mouth. The great depth of Zion Canyon is entirely the result of the down-cutting (erosive) action of a tributary of the Virgin River. The canyon has been cut into the Colorado Plateau near its western border.

*Kings River Canyon.* A canyon remarkable for its combination of narrowness and depth is the Kings River Canyon of the Sierra Nevada Range of southern California. This steep-sided, V-shaped canyon has been carved out of solid granite by the erosive action of the river, aided by relatively little weathering, to the amazing depth of 6900 feet. Profound uplift and tilting of the Sierra earth-block in recent geologic time; volume and swiftness of the water; hardness of the rock; and a liberal supply of grinding tools are the conditions which have favored the development of this canyon.

*The Royal Gorge.* The famous Royal Gorge of Colorado has been (and is being) cut through the recently uplifted Front Range of the Rocky Mountains. It is remarkably narrow with almost vertical walls rising to a height of 1100 feet.

*Grand Canyon of Arizona.* Greatest of all canyons, not only of North America but also of the world, is the Grand Canyon of the Colorado River in Arizona. Its general dimensions are: length, over 200 miles; depth from 4000 to 6000 feet; and width from 7 to 15 miles (Fig. 112). This mighty gash in the earth's crust has been excavated wholly by the Colorado River and some of its shorter tributaries, aided by weathering. Some of the conditions exceptionally favor-

able to this canyon development have been and are: (1) The recent great uplift of the region, providing a thickness of many thousands of feet of rocks to be cut through by the river before reaching grade; (2) the large, very swift river; (3) the abundance of rock fragments constantly carried by the river, thus providing for continually aggressive corrasive action; (4) rock formations hard enough and so arranged that most of them are capable of standing in cliffs or steep slopes;

FIG. 112. A view across the world's greatest canyon. Grand Canyon of Arizona. (Photo by courtesy of U. S. Reclamation Service.)

and (5) the arid climate which causes valley widening to be relatively slow.

The canyon has been carved out during the present period of geological time, and all of the solid rock which once filled the space now occupied by the canyon has been carried away by the Colorado River. Much of the sediment has been deposited in the form of a great fan-shaped delta near the mouth of the river, while the rest has gone into the Gulf of California. The Grand Canyon is still being widened and deepened because the swift, active Colorado River in the bottom of the

canyon is still 2000 to 3000 feet above sea level and far from graded. The maze of side canyons is due to erosion by tributaries to the main river. The numerous buttes and mesas, often of mountainous proportions, rising within the great canyon are erosional remnants which have not been reduced as fast as the rest of the rock mass by erosion.

The rocks of the main or broader part of the canyon are all strata of Paleozoic age. They form a vast pile of nearly horizontal layers reaching a total thickness of nearly 4000 feet as shown in Figure 112. These strata include sandstone, shale, and limestone. The outcropping edges of the formations, which are colored light gray, red and greenish gray, produce the striking color bands so clearly traceable for many miles within the canyon. Outcropping edges of the more resistant formations are in the form of great and small cliffs, while the weaker formations yield steep slopes, often talus covered.

In the narrow, V-shaped inner gorge, through which the river flows in the depths of the canyon, the rocks are mainly dark colored schist, granite, and gneiss of Archeozic age.

At the beginning of the present period of geological time the Colorado Plateau region was an old-age surface on which the Colorado River flowed with a meandering course not far above sea level. Rejuvenation of this old surface by uplift to an altitude of 7000 to 8000 feet in the canyon region greatly revived the erosive activity of the river which has carved the mighty chasm out of the uplifted (Colorado Plateau) region.

**Narrows and Gaps.** River narrows and water gaps are in reality only special types of gorges or canyons. When, during the process of its valley development, a stream takes its course across a belt, or irregular mass, of rock which is relatively more resistant, the valley is there carved out less widely and rapidly than in the weaker rocks just upstream and downstream from the harder rock. Local contractions of river valleys, formed under such conditions are called *narrows*, or *water gaps* if they are very short. Rapids, cascades, and low waterfalls are common in river narrows and gaps. The more resistant rock athwart the channel locally slows up the process of down-cutting, and so there is a tendency for a "temporary base-level-of-erosion" to be established for a greater or less distance upstream from the harder rock.

A few of the many well-known examples of river narrows and water gaps will be cited. The Mohawk River at Little Falls, New York, flows for nearly two miles through a narrow, steep-sided gorge hundreds of feet deep in hard rocks, while for many miles above and

below the narrows the valley has been opened out widely on weak rocks (mostly shales). The lower Hudson River has cut a narrows hundreds of feet deep, and 16 miles long, through hard granite and related rocks. The famous Delaware Water Gap has been cut by the Delaware River through a tilted formation of hard conglomerate, on either side of which there are relatively weak strata.

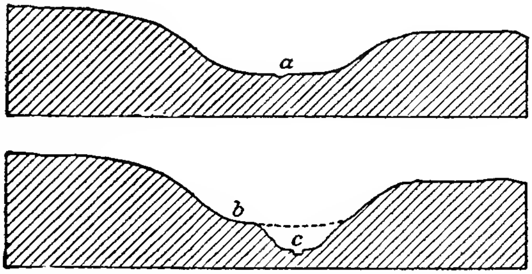



FIG. 113. Diagrams illustrating the development of a rock terrace by a stream. (After U. S. Geological Survey.)

A water gap abandoned by its stream becomes a so-called *wind gap* because of the tendency for the wind to blow with unusual force through the narrow opening in the ridge. Wind gaps very commonly result from stream piracy where a stream flowing through a water gap has its course diverted by a neighboring stream. The principle involved is perfectly illustrated in the vicinity of Harper's Ferry, Virginia (Fig. 110), where the water gap of Beaverdam Creek was converted into a wind gap (called Snicker's Gap) because of the capture of the upper waters of the creek by the Shenandoah River. There are numerous wind gaps in the central and southern Appalachian Mountains similar in origin to Snicker's Gap. Many of them are notches in the tops of the mountain ridges. One of particular interest is Cumberland Gap, on the Kentucky-Virginia line, which is a pass 700 feet deep through the Cumberland Mountain ridge. Several hundred thousand immigrants traveled through this wind gap on their way west in the latter part of the eighteenth century.

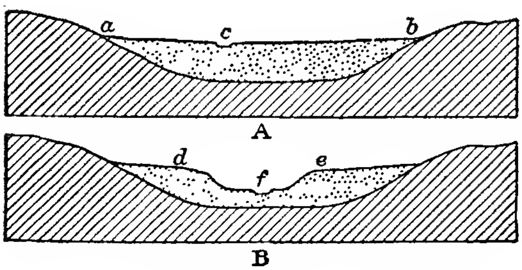



FIG. 114. Diagrams illustrating the development of alluvial terraces. (After U. S. Geological Survey.)

**Stream Terraces.** Along the sides of a valley there may be benches or nearly flat surfaces with steep fronts facing the stream in the valley, and too high to be covered by flood waters. Two or more of them may be arranged one above another in steplike form on both sides of the valley. Such benches, when formed by the action of the stream, are called *stream terraces*. Two of their most common modes of origin will now be explained.

*Rock terraces.* We have already learned that a stream, on approaching grade in its down-cutting process, begins to widen its valley floor notably by meandering back and forth from one side of the valley to the other. A flood plain of such a stream may be covered with more or less stream-deposited (alluvial) soil. Uplift of the region may then take place, causing the revived river to cut a young, steep-sided inner valley (or gorge) into the old flood plain. The remnants of the old valley flat, consisting of bed rock covered with some alluvium, constitute one kind of *rock terraces*. An interesting case is illustrated by Figure 113. After a flat is developed in the bottom of the newer valley, another uplift would inaugurate the development of terraces at a still lower level. Rock terraces also not uncommonly develop during the down-cutting of a valley where resistant layers of horizontal, or nearly horizontal, rocks are worn back on the valley sides less rapidly than weaker layers just above them. A wonderful succession of such rock terraces occurs on a magnificent scale in the Grand Canyon of Arizona, giving rise to what may be called *step topography*.

FIG. 115. Stream-cut terraces in Fraser River valley near Lilloet, British Columbia. (Photo by Calvin.)

*Alluvial terraces.* If, for any reason, a valley becomes partly filled with alluvial sediment, and then the stream in the valley has its erosive activity notably revived by either decreased load or uplift of the land, so-called *alluvial terraces* will develop. Rapid down-cutting by the stream may result in only one terrace level. Often, however, the stream cuts down into the alluvial filling slowly enough to allow the development of meanders. The stream then cuts laterally into the alluvium

first on one side of the valley and then on the other, in each case leaving a flat with a steep face toward the stream. Swinging back to the opposite side of the valley, this time at a somewhat lower level, a new flat is developed and the earlier (higher level) terrace is partly cut away. By such a process a succession of two or more alluvial terraces may be formed (Fig. 114). Excellent examples occur in the Connecticut Valley of New England, and in many other valleys.

**Erosional Remnants.** *General principles.* During the process of general lowering of lands by erosion, it very commonly happens that certain local portions are not cut down as fast as most of the area, and so are left standing out more or less conspicuously above the general level of the country as *remnants of erosion.* There are two important causes of such unequal erosion. One is lack of uniformity of character and structure of the rocks of an area, that is, some portions may be either harder, or more resistant, than others, or less subject to weathering because less broken and fissured by joints or faults. Another cause of erosional remnants is the less rapid erosion in the spaces between streams, this being particularly true in relatively level plain or plateau districts. Erosional remnants are variously shaped and named.

*Towers and pinnacles.* There may be rock *towers, pinnacles,* or *pillars* consisting either of notably harder, isolated masses such as the igneous rock of Devil's Tower, Wyoming, or of the cores of volcanoes (volcanic necks) in Arizona (Fig. 177), or of isolated joint blocks of essentially homogeneous material such as the Cathedral Spires in the Garden of the Gods, Colorado (Fig. 51), or the pinnacles and pillars of lava near Douglas, Arizona (Fig. 53).

*Mesas.* If the rocks are in horizontal layers, or nearly so, and some are harder than others, flat-topped hills or small mountains, called *mesas* (pronounced "maysas") often become erosional remnants. In such cases the flat surfaces are determined by harder layers. Similar isolated masses without flat tops are called *buttes* (pronounced "bewts"). Mesas and buttes are common and typical in many portions of the high, arid to semi-arid plains and plateaus of the western United States, particularly the Colorado Plateau of parts of Arizona, New Mexico, Utah, and Colorado (Fig. 116). Many mesas, buttes, towers, and pinnacles belong in the category of so-called *outliers,* that is, remnants of more extensive bodies of similar rocks separated from the latter by erosion.

*Ridges.* Where erosion proceeds upon a region of highly inclined to vertical (or folded) rock layers or formations which are alternately

hard and soft, the hard belts will, especially during maturity, stand out in relief in the form of *ridges* because erosion cuts down the weaker (softer) rocks more readily, developing valleys in them. This principle is grandly illustrated by the numerous Appalachian ridges approximately parallel with the trend of the mountain range.

*Hogbacks and cuestas.* A *hogback* is an erosional ridge with a long, relatively gentle slope on one side and a short, steep (or precipitous) slope or face on the other side. Such a ridge develops where rock layers (or formations) are moderately tilted with a hard layer lying

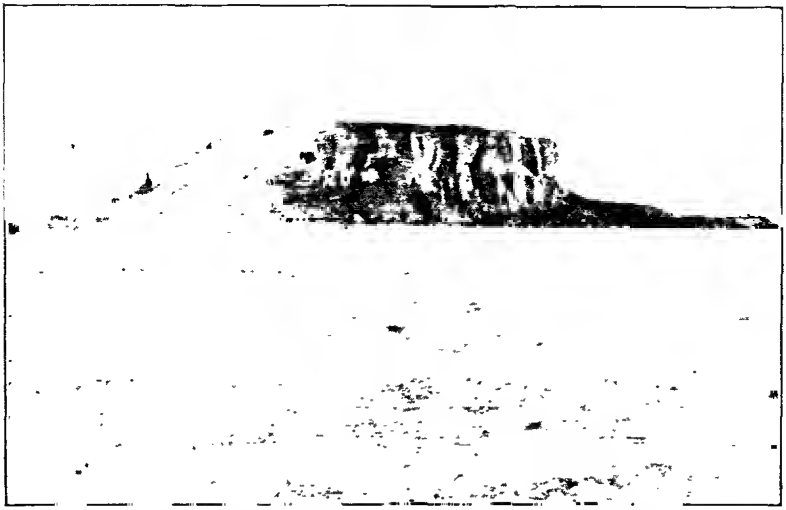


FIG. 116. A mesa carved out of horizontal strata. Near Zuni, New Mexico. (After Darton, U. S. Geological Survey.)

between soft layers. The long gentle slope is caused by the removal of the weak rock from the top of the hard layer, and the tendency of the weak underlying rock to erode (or weather) faster than the hard tilted layer just above it. Hogback ridges, and successions of ridges, are very typically displayed near the eastern base of the Rocky Mountains in Colorado, and also in parts of Arizona and New Mexico.

A *cuesta* is practically the same in principle as a hogback, but on one side its slope is very long and gentle, while on the other side there is an abrupt slope, or even a cliff. Cuestas are well illustrated in the Atlantic and Gulf Coastal Plains of the United States, and, on a grand

scale in the Colorado Plateau country.

*Monadnocks.* A special kind of erosional remnant is the *monadnock* already described. It represents a residual mass of country rock of any shape which has not been reduced to the general level of the peneplain during a late stage in the erosional history of a region.

*Natural bridges.* If, during the process of erosion of a region, a stream perforates the neck of one of its rather deeply entrenched (incised) meanders, a *natural bridge* results, as may be readily understood by examination of Figure 117. The largest natural bridges in the world have originated in this manner, several of them being located in San Juan County, Utah (Fig. 118). Greatest of all is the Rainbow Bridge, which would easily span the dome of the Capitol Building in Washington. It should be clearly understood that natural bridges originate in various other ways than by the action of surface streams.

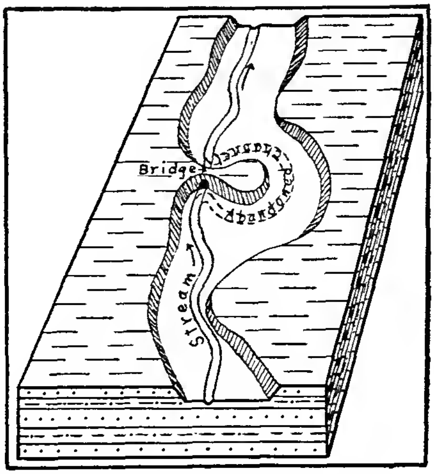


FIG. 117. Diagram illustrating one mode of origin of natural bridges.

**Waterfalls.** *Definitions.* Where a stream rushes over a steep slope in its bed it forms a *rapid.* Where a stream plunges over a vertical, or nearly vertical, rock face it forms a *waterfall.* Between ordinary rapids and true waterfalls, all gradations exist. Waterfalls are sometimes called *cascades* or *cataracts.* Waterfalls originate in many ways. Our present purpose is to consider only some of the most important principles of waterfall development, with emphasis upon the kinds of falls which owe their existence to the more or less direct erosive action of the streams which themselves form cataracts.

*Niagara Falls type.* The most common principle is involved in what may be termed the Niagara type of waterfall, so wonderfully illustrated by Niagara Falls (Fig. 119) which is one of the world's very greatest cataracts. Its tremendous volume of water, divided into two parts (Canadian Fall and American Fall), plunges about 160 feet. In this type of waterfall, the rock formations lie in an approximately

FIG. 118. The great Augusta Natural Bridge in southeastern Utah. (Photo by G. L. Bean, courtesy of the National Park Service.)

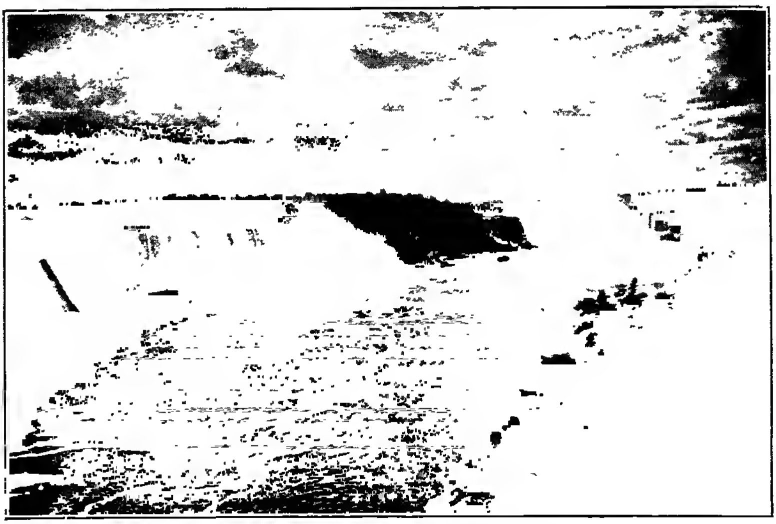


FIG. 119. Niagara Falls. American Fall on the left and Canadian Fall on the right. (Photo by Rau Art Studio, Philadelphia.)

horizontal position with a resistant formation on top of a notably weaker one. At Niagara there is a hard limestone resting upon soft shales in thin layers. The conditions are shown by Figure 120. Under the influence of weathering, and the swirling action of the water, the weaker, underlying rocks are cut away faster than the harder overlying rock, causing the latter to overhang so that blocks of it fall down from time to time, and are mostly carried away by the swift current. The waterfall maintains itself while it retreats upstream and develops a gorge. By this process Niagara gorge, seven miles in length, has been produced since the withdrawal of the great glacier of the Ice Age from the Niagara region—not more than a few tens of thousands of years ago.

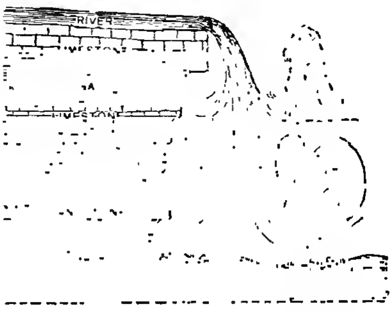


FIG. 120. Structure section at Niagara Falls. (After Gilbert, U. S. Geological Survey.)

*Yellowstone Falls type.* The Yellowstone type of waterfall involves a highly inclined or vertical mass of resistant rock extending across a stream channel, with weaker rock on the downstream (and usually also on the upstream) side of it. At the Great Falls in Yellowstone National Park the river crosses a vertical mass of hard, fresh lava in the midst of other lava which has been weakened by weathering. This hard rock acts as a barrier, permitting rapid down-cutting immediately on its downstream side, but checking erosion on its upstream side. The river, therefore, plunges 308 feet over the vertical face of the barrier (Fig. 121). Waterfalls of this kind commonly develop also in youthful stages of erosion in regions with highly inclined or vertical rock formations of varying degrees of hardness.

*Victoria Falls type.* The Victoria Falls of South Africa, probably the greatest in the world, involves a principle opposite to that of the Yellowstone type, that is, a belt of weak rock lies across the course of the river in the midst of hard rock (lava). The Zambezi River, finding the work of erosion much easier along the belt of weak (highly jointed and fractured) rock, has turned abruptly to follow the weak rock into which it has cut a deep, narrow chasm. The river, which is here over

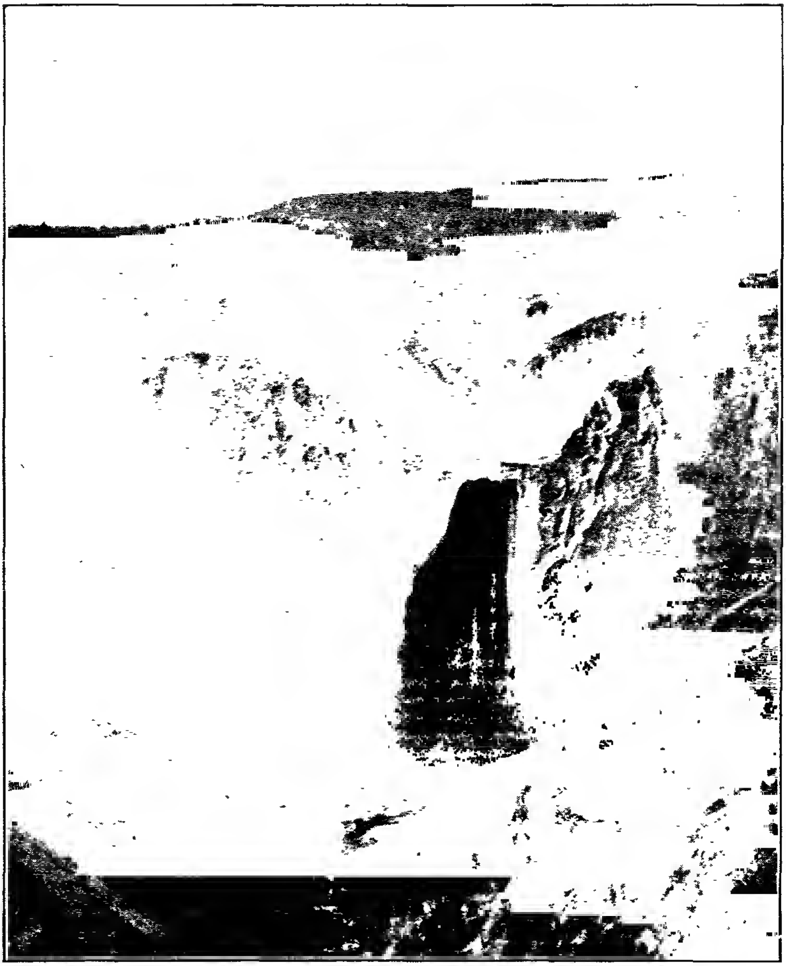


FIG. 121. Great Falls of the Yellowstone River. Height, 308 feet. Yellowstone Park. (Photo by F. N. Kneeland.)

a mile wide, plunges vertically more than 400 feet into the chasm, which is only a few hundred feet wide (Fig. 122).

*Trenton Falls type.* A common type of waterfall results from the removal of joint blocks of rock. Where the rock in the bed of the stream is traversed by well-developed vertical cracks (socalled *joints*), somewhat loosened blocks of rock may be further freed by weathering, and then one by one pushed away by the stream. In this manner a vertical face of rock is produced over which the water plunges. As such a fall retreats by removal of joint blocks, a gorge develops. Taughannock Falls (215 feet high), north of Ithaca, New York, and several falls (one 50 feet high) at Trenton Falls, New York, are good illustrations.

Fig. 122. Detail view of part of Victoria Falls, Zambezi River, South Africa. (Photo by A. J. Orner.)

*Yosemite Falls type.* Another type of waterfall is only indirectly a result of stream erosion. Many of the highest waterfalls of the world belong in this category which we call the Yosemite type on account of the wonderful development of such falls in Yosemite Valley, California. A very active river carved out a deep, steep-sided, V-shaped canyon in the hard granite of the Yosemite region. Then a powerful glacier plowed slowly through the canyon, broadening, and somewhat deepening it, and making its walls precipitous by cutting them back. On the melting of the glacier, various tributaries were forced to enter the main valley by plunging over great granite cliffs. At Yosemite Falls, a stream plunges the amazing distance of 1430 feet vertically over such a granite cliff, this being probably the highest true waterfall in the world. The same water, after descending a very steep slope for 800 feet, plunges 320 feet vertically to the floor of the valley (Fig. 123). Bridalveil Falls in the same valley and of similar origin is 620 feet high. Throughout the mountainous portions of North America and Europe which were occupied by glaciers during the Ice Age, the Yosemite type of waterfall is common. Examples are a fall 1200 feet high (though not wholly vertical) in the Yoho Valley of British Columbia, and one 900 feet high in the Lauterbrunnen Valley of Switzerland.

FIG. 123. Yosemite Falls, California. Upper portion, 1430 feet; lower portion, 320 feet. (Photo by F. N. Kneeland.)

FIG. 124. A stream bed of limestone honeycombed with potholes. Near Boonville, New York.

**Potholes.** Where rock fragments are given a rapid, swirling motion by an eddy in a swift stream they often wear round or cylindrical excavations, known as *potholes*, in the bedrock of the stream. Such an eddy must of course maintain itself in one place long enough for the grinding action to develop the pothole which may be from a few inches to 25 feet or more in both diameter and depth. As the grinding materials, consisting of sand, gravel, or even boulders, wear out, new materials are supplied by the stream. Local portions of stream beds may be honeycombed with potholes (Fig. 124).

# CHAPTER VIII

## GLACIERS AND THEIR WORK

### Geological Importance of Glaciers

When a body of ice, which has been formed from compacted snow, begins to spread or flow from its place of accumulation it is called a *glacier*. In short, a mass of flowing ice may be called a glacier. Glaciers vary in size from a fraction of a square mile to many hundreds of thousands of square miles.

Much of the land of the earth is, during at least part of the year, covered by snow or ice, and considerable areas are perpetually covered. Moisture, locked up in the form of snow and ice, would tend to accumulate indefinitely in regions of perpetual snow if it were not for the important part played by glaciers in returning much of this moisture to lower and warmer levels.

Glaciers, like rivers, perform their principal geological work by erosion of the land, and by transportation and deposition of rock débris. Although such work accomplished by glaciers is, on the whole, much less than that of streams, it is, nevertheless, of great importance. Streams have been constantly at work upon most of the lands for tens of millions of years, while glaciers have been much more restricted both in time and place. Water, wind, and ice are the three great agents which operate to modify the lands of the earth by the processes of erosion and deposition.

### Types of Glaciers

According to their form, size, and position, we may recognize five types of glaciers as follows: (1) *Valley glaciers*, (2) *hanging glaciers*, (3) *piedmont glaciers*, (4) *ice caps*, and (5) *continental glaciers*.

**Valley Glaciers.** These are often called *alpine glaciers* because of their typical development in the Alps where they were first carefully studied. They are streams of ice flowing through valleys, and fed from catchment basins of snow located in regions of perpetual snow. They may have tributaries but, as compared to rivers, these are relatively few in number. Of all the types of glaciers, valley glaciers are the most

abundant. They range in length up to about nine miles in the Alps, and up to 40 or 50 miles in southern Alaska. Valley glaciers very commonly attain thicknesses of from a few hundred feet to a thousand feet or more, and widths of from one-fourth of a mile to several miles.

**Hanging Glaciers.** These are sometimes called *cliff glaciers.* They are poorly formed, usually small, glaciers which occupy depressions or steep clefts high up on mountainsides and do not descend into valleys. They sometimes move to the edge of a cliff or a very steep slope and break off. Where a glacier of any kind, but especially a hanging glacier,

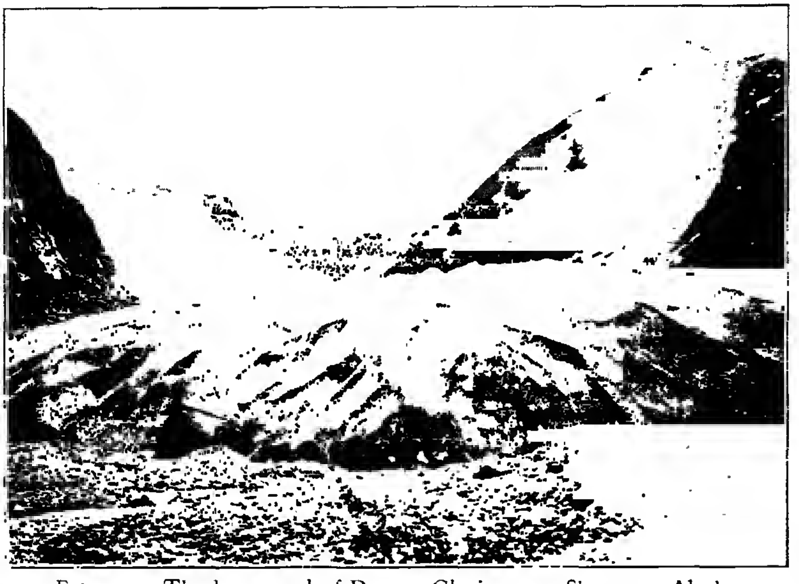


FIG. 125. The lower end of Denver Glacier near Skagway, Alaska.

moves to the edge of a cliff or a steep slope and breaks off, the fragments which fall to the base of the slope may freeze together again and form a *reconstructed glacier.* The Lefroy glacier near Lake Louise, British Columbia, is a good example. There are many fine examples of hanging glaciers in the Rocky Mountains of southern Canada and northern United States, and in the Cascade Mountains of Washington and Oregon (Fig. 126).

Hanging glaciers show all stages of transition to true valley glaciers. Such intermediate types are wonderfully displayed on the great volcanic cone of Mt. Rainier, Washington, whose very steep sides support a system of nearly 50 square miles of glaciers.

**Piedmont Glaciers.** A piedmont glacier is formed by the coalescence of the spreading ends of valley glaciers where they flow down mountains and out upon relatively level country. It is, in effect, somewhat like a lake of ice at the foot of a mountain. The Malaspina Glacier, covering 1500 square miles at the foot of great Mt. St. Elias in southern Alaska,

FIG. 126. Hanging glaciers near Lake Chelan in the Cascade Mountains of Washington. (Photo by U. S. Reclamation Service.)

is a fine large example. It has a nearly level surface, and it moves very slowly. Its border portions are almost completely concealed under rock débris and even forest growths. Muir Glacier in Alaska is intermediate in general character between a valley glacier and a piedmont glacier. It covers hundreds of square miles (Fig. 127).

**Ice Caps.** In certain high-latitude regions, such as Scandinavia, Iceland, and Spitzbergen, glacial ice may accumulate on relatively level plains or plateaus as ice sheets which slowly spread or flow radially from their centers. These are called ice caps. They seldom cover more than a few hundred square miles. If properly situated, they may send small alpine glaciers down radiating valleys.

**Continental Glaciers.** These are *ice sheets* of great extent, usually covering many thousands of square miles. They are, in principle, much

FIG. 127. A general view of the great Muir Glacier, Alaska, showing its terminal cliff (several hundred feet high) in tide water. (Photo by H. F. Reid.)

like ice caps, only they are larger. A vast ice sheet now covers fully 500,000 square miles of Greenland, and its motion is outward in all directions toward the sea. It sends off many tongues of ice into the tide water. A still greater ice sheet covers much of the south polar region to an extent of probably at least several million square miles. The Greenland and Antarctic ice sheets are the only ones at present large enough to be classed as continental glaciers. In times past, however, still greater expanses of glacial ice are known to have occupied certain portions of the earth. Thus during the Ice Age of Quaternary time a vast glacier covered about 4,000,000 square miles of North America as described in Chapter XXIV, Part II of this book.

## Existing Glaciers

Millions of square miles of the earth are covered with glaciers ranging in size from a fraction of a square mile to millions of square miles. Greatest of all are the vast ice sheets, or continental glaciers, occupying much of Greenland and Antarctica. Ice caps of less extent occur in the Arctic Islands, Spitzbergen, Iceland, and southern Scandinavia.

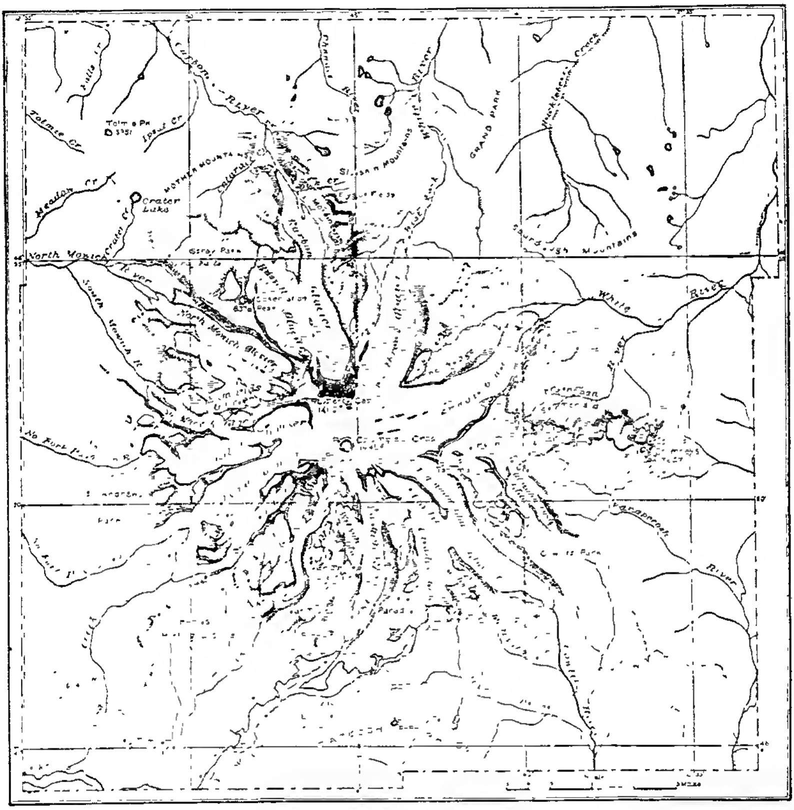



FIG. 128. Map showing the great system of 50 square miles of radiating glaciers on Mt. Rainier, Washington. (After U. S. National Park Service.)

Piedmont glaciers, like ice caps, are not very common, their best representation being probably in southern Alaska.

Of all the types of glaciers, the valley or alpine type is by far most abundant. They are best known in the Alps where there are probably no less than 2000 of them. Most of them are less than one or two miles long; a few are from three to five miles long; and one—the Great

Aletsch—is over nine miles long. In Europe, the Pyrenees, Carpathian, Caucasus Mountains, and the mountains of Norway also support numerous valley glaciers, those of Norway and the Caucasus being especially large.

The great Himalayas of southern Asia support a magnificent system of very large, high-altitude, valley glaciers, many of them from 5 to 30 miles long. Africa contains few if any glaciers.

The Andes Mountains of South America support many valley glaciers, some small ones at very high altitudes lying practically at the equator. There are many large valley glaciers in the southern Andes.

There are no glaciers in the eastern two-thirds of North America, but the western portion of the continent contains many of them. There are tens of thousands of glaciers in southern Alaska, most of them by far being valley glaciers which range in length up to 50 miles, and in width up to five or six miles. Dozens of them flow down the mountains into tide water where they break off to form icebergs. Southern Alaska is a wonderland of lofty mountains, vast fields of perpetual snow, and numerous, great valley glaciers (Figs. 125 and 127). Valley glaciers of fair size, and hanging glaciers, are common in the southern Canadian Rockies. In the northern Rockies of the United States, from Colorado into Montana, there are scores of small glaciers, mostly of the hanging-glacier type, especially in Glacier National Park. The Cascade Mountains of Washington, Oregon, and northern California, especially the higher peaks such as Mt. Rainier, Glacier Peak, Mt. Hood, Mt. Jefferson, and Mt. Shasta, support numerous glaciers ranging from hanging glaciers to true valley glaciers from a fraction of a mile to five miles in length. Some small hanging glaciers occur in the southern half of the Sierra Nevada Range of California. Certain high peaks of Mexico support small glaciers.

## The Great Ice Age

The Quaternary is the latest great period of earth history, and it still continues for it has led up to the present-day conditions. This period was ushered in by the spreading over much of northern North America and Europe of vast ice sheets which must take rank as one of the most interesting and remarkable occurrences of geological time. During several other periods of geological time, glacial ice was more or less extensively developed, particularly during late Paleozoic time, but the term "Ice Age" refers to that of the present (Quaternary)

period. Existing glaciers are but remnants of the once much greater glaciers of the Ice Age.

## Origin of Glaciers

**Perpetual Snow Fields.** Glacial ice is derived from snow. Two conditions are necessary for the formation of glaciers—low temperature and sufficient snowfall. These conditions obtain in perpetual *snow fields*, that is, areas over which the snow persists season after season, and year after year. In such snow fields there is a tendency for snow to accumulate faster than it can be removed by melting or evaporation, and the excess snow is removed by being transformed into glacial ice as explained below. Some snow fields are too small to produce enough ice for glacier motion.

The line above which snow is always present is called the *snow line*. It is, in other words, the lower edge of a snow field. Snow fields occur in all the regions already mentioned as containing glaciers. They are not uncommon, usually at relatively high altitudes, on all the great land divisions of the earth except Australia, which has none, and Africa, whose few small snow fields are confined to a group of high mountains in the east-central part of the continent.

In the Antarctic, and in parts of the Arctic, regions the snow line is at or near sea level, while in the equatorial region it is from 15,000 to 18,000 feet above sea level.

**Change of Snow into Ice.** Every perpetual snow field is also, in part at least, a field of ice. As the snow of such a field accumulates it gradually undergoes a change, especially in its lower portions, first into granulated snow, called *névé*, and then into solid ice. In the late winter and early spring, snow banks in the northern United States often exhibit such a granular appearance. In the snow field the névé grades downward into porous ice, and finally into solid ice.

The transformation of snow through névé to ice is effected mainly by the weight of overlying snow which squeezes together and compacts the snow crystals, and by rain or melting snow working down into the snow there to freeze and fill spaces between the snow crystals. When the ice beneath a snow field becomes deep enough (usually at least several hundred feet), the spreading action or flowage develops, and a glacier is formed. Repeated falls of snow over the gathering ground of the glacier keep up the supply of glacial ice.

## Movement of Glaciers

**Rate of Movement.** The average rate of movement of glaciers is far less than that of rivers. Many observations have shown that the average rate of movement of the glaciers of the world is not more than a few feet per day. Most of the valley glaciers of the Alps move from one to three feet per day, and this is about an average rate for glaciers of this type. A most exceptional case is a certain glacier, extending as a tongue of the great Greenland ice sheet, whose rate has been found to be 60 to 70 feet per day. Some of the very large glaciers of Alaska move at rates of from 4 to 40 feet per day. A glacier advances across country only when its rate of movement is greater than its rate of melting.

**Laws of Glacier Motion.** The nature of glacier motion is by no means simple. It involves *differential motion* in a rather complex sense of that term. Brief mention of most of the so-called "laws of glacier motion" will serve to make clear the complicated nature of the movement. These laws, which apply most typically to valley glaciers, are as follows:

1. A glacier, to a greater or less extent, actually glides or slides over the earth's surface. This is abundantly proved by the eroded, and often polished and striated rock surfaces left by glaciers.

2. The top portion of a glacier moves faster than the bottom, because of friction of the glacier on its bed. This has been proved by observing the change in position of a vertical line of pegs driven into the steep side of a valley glacier.

3. The middle portion moves faster than the sides because of friction of the glacier against its containing banks. This is easily proved by observing the changing position of a row of marked objects placed across a valley glacier.

4. The velocity increases with steepness of slope of the bed. This has been proved particularly for certain glaciers in the Alps. It must be so because gravity is the ultimate force which causes the motion.

5. The velocity increases with the thickness of ice. This again is due to the fact that the force of gravity is more effective in causing movement if a body of glacial ice on a slope is relatively thick.

6. The velocity increases with temperature. In warm weather a glacier moves faster than in cooler weather, that is, it moves faster when it is melting and contains more water.

7. Velocity increases with straightness of course. A glacier flows

less rapidly through a crooked valley because the friction is greater as the ice current rounds the curves.

8. Velocity diminishes with roughness of bed. The motion of the glacier is retarded by being forced over inequalities or obstacles in its bed.

9. Velocity diminishes with amount of load in the basal portion. This is because of increased friction of the glacier on its bed.

10. The line of greatest velocity is more winding than that of the glacial channel. Just as in a river, the tendency also in a winding glacier is for the line of greatest current to swing back and forth from one side to the other.

11. A stream of ice does not conform to minor irregularities of the sides of the channel. A glacier several hundred feet thick may move past the end of a tributary valley without flowing into the latter to seek the general ice-level. In this respect, glacier movement is very different from that of water.

Except for the force of gravity which inaugurates the movement, the cause of glacier motion is not yet definitely known. Several theories have been advanced, but it would carry us into too great detail to discuss them in this book.

## Lower Limits of Glaciers

We have already learned that glaciers almost invariably originate in regions of perpetual snow. A rare exception to this rule might be the formation of a reconstructed glacier below the snow line. Under favorable topographic conditions, most glaciers of considerable size flow down to greater or less distances below the snow line. This is particularly true of valley glaciers. Many small hanging glaciers move little if any below the snow line. Piedmont glaciers generally form well below the level of the snow field. Ice caps often send tongues of ice below the edge of the snow field. Continental glaciers usually lie very largely within snow fields, though around their borders the ice may extend beyond the snow line.

Valley glaciers not uncommonly move some miles beyond, and several thousand feet below, the line of perpetual snow. A comparison of altitudes of some examples of lower limits of glaciers with the altitudes of the snow line in the same regions as above listed will be instructive in this connection. In the southern Sierra Nevada Range of California the lower limit of glaciers is about 12,500 feet. On Mt. Shasta in

northern California it is about 9000 feet. The lower limit in the Cascade Mountains of Washington is about 4500 feet, while at the same latitude in the Rocky Mountains of Montana it is about 6500 feet, the difference being due mainly to the greater snowfall in the former region. In southern Alaska a number of the great glaciers move down to tide water, there to break up in the form of icebergs. Glaciers of southern Greenland reach the sea. In the Alps the lower limit is about 4000 feet. A remarkable case is in New Zealand where large glaciers on South Island flow down into sub-tropical forests of tree ferns.

FIG. 129. A great transverse crevasse in South Sister Glacier, Cascade Mountains, Oregon. (Courtesy of U. S. Forest Service.)

The position of the lower end of a glacier depends upon the relation between rate of movement and rate of melting and evaporation of the ice. When rate of movement predominates over rate of evaporation and melting, the end of a glacier advances, and vice versa. A rather delicate balance will cause the end of a glacier to remain stationary for a time.

Most of the glaciers of Europe and North America are now retreating. Thus the Rhone Glacier in the Alps has retreated a considerable fraction of a mile in the last 30 years. The Illecillewaet Glacier in the Selkirk Mountains has retreated hundreds of feet during the last 20 years. Nisqually Glacier on Mt. Rainier, Washington, was about a fifth of a mile longer in 1885. The tide-water front of the great Muir Glacier of Alaska has retreated several miles in the last 30 years.

## Crevasses in Glaciers

The surface of a glacier is usually very rough, irregular, and broken, often making travel over it difficult, or even dangerous. The roughness is due in part to irregular melting of the ice; to streams of water

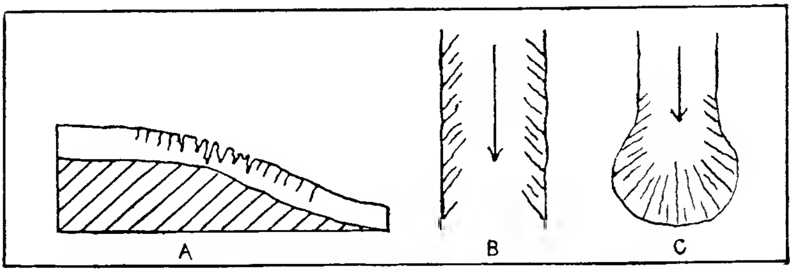



**Fig. 130.** Sketches showing origin of crevasses in glaciers. A, structure section showing transverse fissures; B and C, ground plans showing marginal and longitudinal fissures.

which melt and erode channels in the ice; and to irregular accumulations of rock débris, called moraines, described beyond. The major irregularity and roughness of surface is, however, due to the presence of numerous small and large cracks and fissures which will now be described and explained. They are of three general types. They vary in width up to 20 feet or more, and in depth to hundreds of feet.

Much like molasses candy, ice tends to crack when subjected to a relatively sudden force, particularly a force of tension. Thus where there is a rapid increase in slope across the bed of the glacier, the ice may not be able to mold itself over the salient without rupture, and *transverse crevasses* develop across the glacier (Fig. 129). This is because tension in the upper portion of the glacier is greater than in the lower portion over the salient in the bed (Fig. 130). A rapid change of slope of only a few degrees is usually sufficient to cause transverse crevasses. Owing to the forward motion of the ice, old crevasses often close up, and new ones develop over the salient.

Due to the greater velocity of the central portion of a valley glacier, stresses and strains set up in the marginal portions often cause *marginal crevasses* to develop. Such cracks usually extend obliquely upstream from each margin of the ice well into the glacier at angles of approximately 45° (Fig. 130).

Where a glacier spreads laterally in a broader portion of a valley, or where it terminates and spreads out on a nearly flat surface, *longitudinal crevasses*, that is, cracks roughly parallel to the direction of ice-flow, usually develop. In such cases the ice by fracturing yields to the force of tension which is caused by relatively rapid spreading (Fig. 130).

Fig. 131. A bergschrund at the head of a glacier. Swiss Peak, British Columbia. (Photo by L. G. Westgate.)

A type of crevasse not really within the body of the glacier should be mentioned. This is the *bergschrund* which develops at the head of the glacier where the glacier motion begins. This fissure (or series of them) forms where the thick body of ice, névé, and more compacted snow of the snow field draws away from the thinner, less compacted snow of the upper margin of the snow field (Fig. 131). The bergschrund will be referred to again in the discussion of glacier erosion.

## Moraines

Most glaciers carry, or drag along, more or less rock débris ranging in size from very finely divided material to great boulders. Such débris is transported by a glacier either on its surface, or within it, or in or under its bottom portion. The term *moraine* applies to all material gathered, transported, and deposited by glaciers. Morainic material is represented partly by rock fragments which are rolled or washed down upon the glacier, and partly by rock fragments eroded by the glacier from the bed and sides of its channel. Morainic material carried on top of the glacier may be called *superglacial:* that frozen within it, *englacial;* and that in and just under its bottom portion, *subglacial.*

The superglacial débris is mostly of two classes—lateral and medial. Where it is arranged along the sides of the glacier it is called a *lateral moraine*. It consists mainly, or wholly, of material which has rolled or washed down upon the margins of the glacier from its bordering rock walls or sides. It is usually most conspicuous toward the end of the

glacier where it forms ridges of earth from a few feet to a hundred feet, or more, high. A *medial moraine* is a belt of rock débris on the surface of the glacier, well away from its margin. It may or may not be in the middle of the glacier. It nearly always results when two glaciers flow together, so that two adjacent lateral moraines (one from each glacier) unite to form a medial moraine. A trunk glacier, formed by the union of several tributaries, may show several medial moraines.

*Englacial material* results partly from rock débris which accumulates on the surface in the catchment basin, and is buried under new falls of snow which change to ice, and partly from débris which falls into crevasses in the glacier farther down its course. Englacial material may travel miles through the body of a glacier, and then emerge at or near its terminus. Marked objects thrown into the sources (catchment basins) of glaciers many years ago have been found to emerge at or near the lower ends of the glaciers. When, through melting and evaporation of the top ice, some of the englacial material appears at the surface of the glacier, it becomes *superglacial material.*

*Subglacial material*, also called the ground moraine, is lodged within, or dragged along just under, the bottom of a glacier. It consists of superglacial and englacial materials which make their way to the bottom, together with materials picked up by glacier erosion. The greatest portion of all morainic material is carried in the bottom portion of a glacier.

All rock débris—superglacial, englacial, and subglacial—carried along by a glacier ultimately tends to reach its terminus where it accumulates to form the *terminal moraine.* Such a moraine becomes most conspicuous when the terminus of the glacier remains practically stationary for some time (Fig. 138).

## Drainage of Glaciers

In mild weather, a glacier nearly always has streams of water upon it. Most of this water results from melting of the ice, but some of it may flow down the valley sides, and thence upon the glacier. Most of these streams are very temporary, and they usually do not flow far before pouring into crevasses, or over the sides or end of the glacier. Some of the water follows englacial channels for a time, and some of this englacial water may issue from the sides of the glacier above its bottom in the form of springs. The general tendency is, however, for the water to accumulate in the form of a stream at the bottom of the glacier, and to issue at or near the terminus of the latter, often from a

tunnel (Fig. 125). The water of such a subglacial stream is characteristically turbid and whitish because it is charged with very finely ground

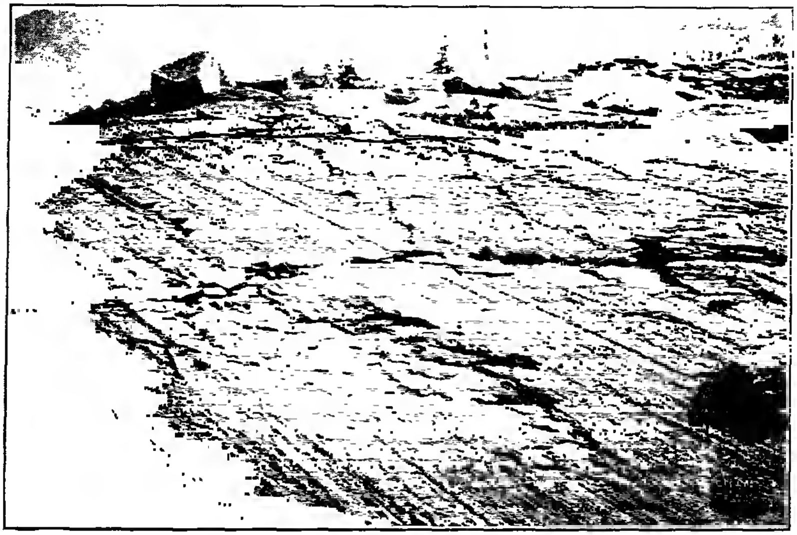


FIG. 132. A glaciated ledge of sandstone high up in the Rocky Mountains. Glacier Park, Montana.

particles of fresh, unweathered rock. Ordinary streams in flood are usually brownish or yellowish because charged with weathered material rich in oxide of iron.

## Glacial Erosion

**How Glaciers Erode.** Glacial ice, like running water, can accomplish more or less erosion of loose and soft rock materials. But, like water, ice has considerable power to erode relatively hard rock only when it is properly supplied with tools.

An important process of glacial erosion is *corrasion*, that is, the rubbing and grinding action of rock fragments either frozen into the bottom and sides of the glacier, or situated just underneath it. Much of the work of erosion is, then, accomplished not by the ice itself, but rather by the rasping, grinding, and rubbing action of the rock fragments carried along by the glacier. Rock surfaces which have been subjected to glacial corrasion are characteristically smoothed and usually more or less scratched, striated, or grooved (Fig. 132). Such scratches and grooves are known as *glacial striae*. A glaciated rock surface of

this kind constitutes one of the best proofs of the former presence of a glacier in a region, and the striae indicate the direction of the glacier movement.

Another important process of glacial erosion is *plucking* or *pressure*. This consists in separating from the bedrock, and pushing along, blocks of rock already more or less loosened by joint cracks. Highly jointed rocks are, therefore, most susceptible to glacial plucking. Such joint blocks, as well as any other boulders and pebbles, which are rubbed

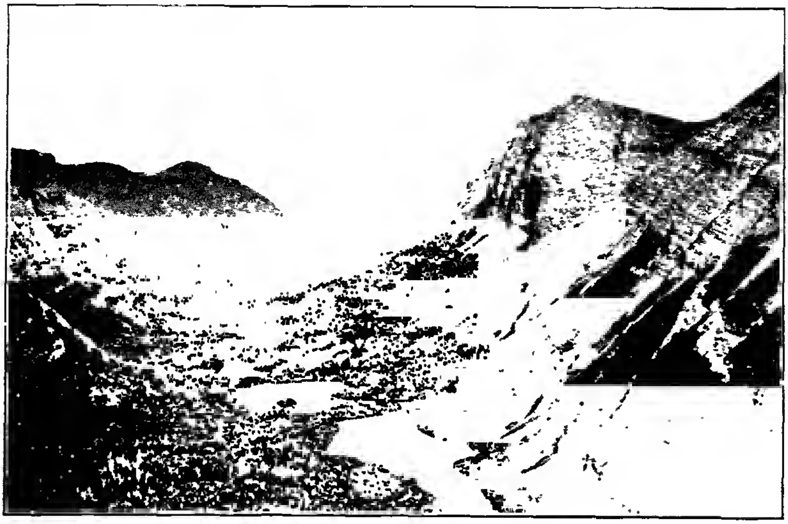


FIG. 133. A U-shaped glaciated canyon in the Rocky Mountains. Swiftcurrent Valley, Glacier Park, Montana.

either against the bedrock, or against each other, by the movement of the glacier, often become faceted and striated.

**Efficacy of Glacial Erosion.** Considering the present and past condition of the earth, the total work of ice erosion as compared to that of running water is slight, because glacial erosion is, and has been, much more restricted in its action both in space and time. During the last 50 years various opinions have been expressed in regard to the efficacy of glacial erosion. Some geologists have ascribed great erosive power to glaciers, while others have considered them to be weak erosive agents. The present consensus of opinion is that, under reasonably favorable conditions, glaciers accomplish a truly important work of erosion.

Conditions for ice erosion are exceptionally favorable where a thick glacier, shod with numerous fragments of hard rock, moves over rela-

tively soft, or highly jointed, rock because the grinding tools are hard and abundant; the work to be done is easy; and the pressure of the ice on the bedrock is great.

A remarkable example of the power of a valley glacier to erode very hard rock is the famous Yosemite Valley of California. This valley is seven miles long, several thousand feet deep, and broad-bottomed. The rock is wholly a hard granite, but it is unusually highly jointed. Just before the Ice Age, the site of the Yosemite Valley was a V-shaped canyon about 3000 feet deep. Then a big valley glacier moved through the canyon, filling it to overflowing. The great depth of ice, causing tremendous pressure (and hence effective corrasion) on the bottom and lower sides of the canyon, combined with the unusually highly jointed

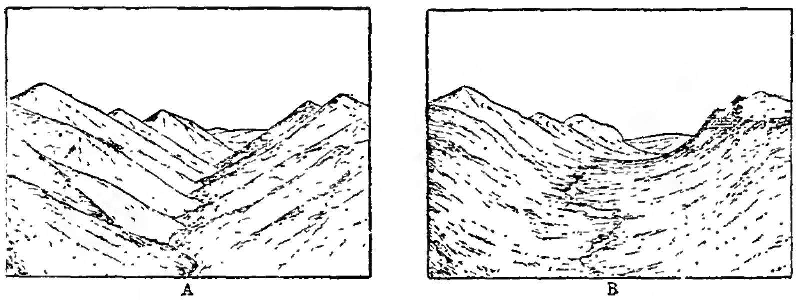



FIG. 134. Diagrams showing a stream-cut valley (A) as it appears after glaciation (B). (After U. S. Geological Survey.)

nature of the rock, so greatly facilitated the work of erosion that the V-shaped canyon was deepened hundreds of feet, and its sides were notably cut back and greatly steepened.

**Characteristics of Glacial Valleys.** A mountain valley through which a thick glacier has flowed relatively recently shows certain unmistakable evidences of the former presence of the ice. Some of the principal characteristics of glacial valleys will now be briefly described.

(1) A valley which has been vigorously glaciated has a broad bottom, and very steep to vertical sides. In other words, it has a U-shaped cross-section or profile instead of the characteristic V-shaped cross-section of a valley vigorously eroded by a stream. This is because a glacier not only erodes the bottom of its valley, but also because it very actively cuts back the sides of the valley, especially toward their bottoms where the ice pressure is greatest. Thus the valley is deepened, its sides are notably cut back and much steepened, and its bottom is much broadened

(Fig. 134). Yosemite Valley (already described) with its great precipitous walls and broad floor is a wonderful example. There are many other examples in the Sierra Nevada, Cascade, and Rocky Mountains (Fig. 133), and in Alaska.

(2) Many of the glacial valleys (or canyons) in the mountains just mentioned are much straighter, and more open for long distances, than stream-eroded valleys (or canyons) would be. This is because a glacier has a much stronger tendency to take a straighter course than has a river, and so the lower ends of the ridges (spurs) which project down into the valley alternately from opposite sides are truncated by glacial erosion (Fig. 134).

(3) We have already learned that stream-cut tributary valleys very typically join their main-stream valleys *at grade*, that is, at practically the same level. In a glacial valley, however, the tributary valleys show typically a *discordance* of position, that is, they join the main valley much above its bottom and are, therefore, called *hanging valleys*. This is because the lower ends of the tributary valleys are cut back during the process of valley widening by the action of the glacier in the main valley. Even if glaciers occupy the tributary valleys, they are usually too small to cut down their beds as fast as the main glacier. Streams in such tributary hanging valleys usually enter the main-valley streams by waterfalls or cascades. Hanging valleys with waterfalls are grandly exhibited in the Yosemite Valley. Many other examples occur in the Sierra Nevada, Cascade, and Rocky Mountains, and in southern Alaska, Norway, and the Alps.

(4) A less common feature of glacial valleys is that large glaciers entering the sea may erode their valleys hundreds of feet below sea level. This is because the moving ice is able to displace the water until its depth becomes so great that the ice is buoyed up and broken off. A number of large Alaskan glaciers which enter arms of the sea are now at work deepening their valleys hundreds of feet below tide level. Rivers can cut their channels but very little below sea level.

In this connection mention should be made of certain deep-water, narrow arms of the sea with high steep walls, called *fiords*. They are exhibited on grand scales in Norway and southern Alaska where they are often 10 to 75 miles long, and several thousand feet deep; and on a less grand scale in Maine. All, or nearly all, of them have resulted from erosion of river valleys by glaciers followed by notable subsidence of the land. They are usually too deep to be accounted for by glacial

erosion alone. The maximum depth of water in Norwegian fiords is commonly from 1000 to 4000 feet.

**Cirques.** The heads of glacial valleys are very commonly characterized by big, steep-sided, amphitheatre-like basins known as *cirques*. As we have already mentioned, the main body of snow, névé, and ice of the snow field at the head of a valley glacier tends to pull away from the snow and névé of the upper slopes, leaving a deep crevasse called the *bergschrund* in which the bedrock is more or less exposed (Fig. 131). During the warm days of summer, water fills the joint cracks and crevices in the rocks down in the bergschrund, and during the much colder

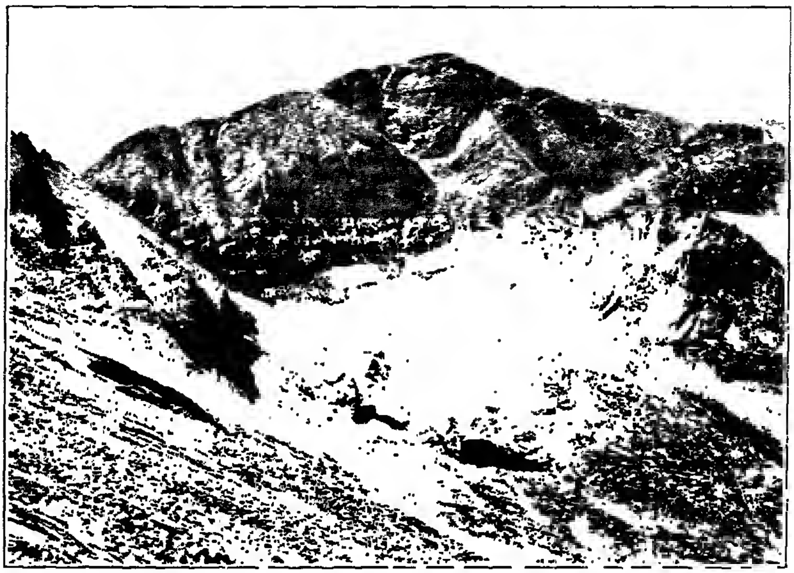


FIG. 135. A typical cirque about 3000 feet deep on the west side of Long's Peak, Colorado.

nights this water freezes, forcing apart and loosening some of the joint blocks. Such rock fragments accumulate in the bottom of the bergschrund where, in the later colder season, they are enveloped in ice and in névé formed from new snowfalls. The rock fragments are thus frozen into the head of the glacier and carried along by it. This quarrying or excavating operation, which is repeated season after season, is most effective toward the bottom of the bergschrund, and so the sides of the valley head are cut back and greatly steepened, forming a cirque.

Cirques, now free from ice or nearly so, are abundant in the Sierra Nevada, Cascade, and Rocky Mountains (Fig. 135), in southern Alaska,

and in the higher mountains of Europe. They are commonly from one fourth of a mile to a mile or more wide, with steep to precipitous walls from 500 to 3000 feet high. Occasionally cirques occupy the positions of hanging valleys, excellent examples occurring in Glacier National Park, Montana. Cirques constitute striking features of the landscape in these and other recently glaciated mountains. They often contain small lakes.

Two cirque walls may be cut back toward each other from opposite sides of a mountain mass until only a very sharp divide, known as a *knife-edge* ridge, is left between the cirques. A knife-edge ridge may also develop where glaciers in two parallel valleys erode and steepen the valley sides until only a very sharp divide separates the valleys. If three or more heads of glaciers cut cirques into a mountain mass from several sides at once, a high, pyramid-shaped rock mass, commonly called a *matterhorn,* may result. The type example is the famous Matterhorn of the Alps. Matterhorns are common in Glacier Park, Montana (Fig. 136).

## Glacial Deposits

**The Drift.** We have already learned that glaciers transport large quantities of rock débris either on their surfaces, or within them, or dragged along at their bottoms. It is heterogeneous material ranging

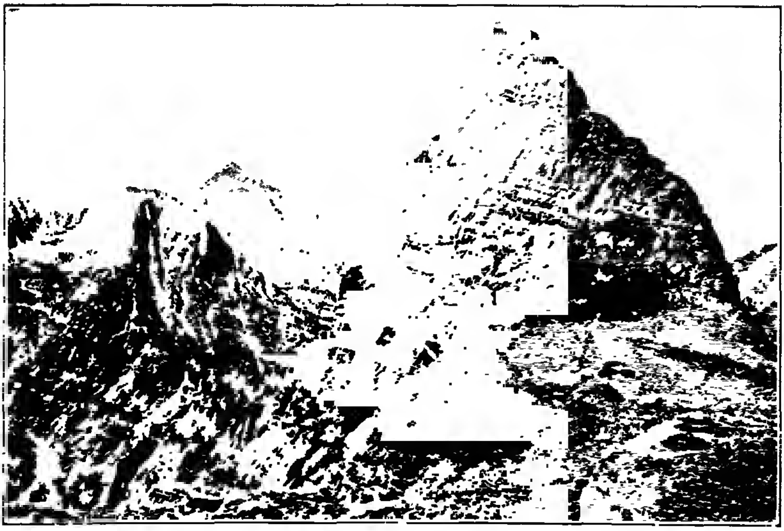


Fig. 136. Matterhorn Peak in Glacier Park, Montana. (Copyright photo by R. E. Marble, Glacier Park, Montana.)

from the finest clay, through sand and gravel, to boulders weighing many tons. Some of these materials may be deposited during the slow advance of a glacier, but such materials are again very largely eroded and carried along by the advancing ice. Most of the deposits, not again disturbed by the ice, are laid down during the retreat of a glacier, and these are of chief interest to us because they are the ones which are so wide-spread as a direct result of the recent great Ice Age. Most of the deposits left by the glaciers of the Ice Age are remarkably intact except for relatively little post-Glacial weathering and erosion.

The general term applied to all deposits of glacial origin is *drift*, this name having been given when, before the discovery of the fact of the Ice Age, such deposits were regarded as having been carried (or drifted) over the country by floods and icebergs. Much of Canada and most of the northern United States as far south as New York City, Pittsburgh, St. Louis, and Pierre, South Dakota, are covered by drift from a few inches to several hundred feet thick. It is not shown mainly where bedrock is exposed; where lake and river waters are present; or where there are post-Glacial river and lake deposits. The drift bears unmistakable evidences of its glacial origin. Some of its material has been transported hundreds of miles, as proved by tracing certain types of rocks in the drift to their parent ledges. An important characteristic of the drift is that it rests upon the bedrock by sharp contact, and usually contains at least some material different from the bedrock, showing that it is transported, and not residual, material.

There are in general two classes of glacial deposits, namely, the unstratified *ice-laid deposits* which are left by the ice unaided by the action of water, and the stratified *fluvio-glacial deposits* which are carried and deposited by waters in, or emerging from, glaciers. These two classes will now be briefly described.

**Ice-laid Deposits.** *Ground moraines.* These consist of heterogeneous, unstratified rock débris deposited underneath a glacier, especially during its melting and retreat (Fig. 137). When it is mostly very fine material with pebbles or boulders scattered through its mass, it is called *till* or *boulder clay*. The pebbles and boulders are often characteristically faceted and striated as a result of having been rubbed and ground against the bedrock. Ground morainic material is exceedingly widespread in the great glaciated region of North America.

*Terminal Moraines.* Whenever the terminus of a glacier remains in a relatively stationary position for a considerable time much rock débris carried by the glacier accumulates around its end, forming a *terminal*

*moraine* (Fig. 138). Such a moraine, especially as left by the great ice sheets of the Ice Age, is a more or less distinct range of low hills, with depressions between the hills, consisting of very heterogeneous, generally unstratified débris, though at times waters emerging from the glacier may have caused some local stratification. Valley glaciers often leave looplike terminal morainic ridges across valleys or at their mouths. A great terminal moraine is more or less clearly traceable across the United States where it marks the southernmost limit of the vast glaciers of the Ice Age. On Long Island it is wonderfully well shown by the

FIG. 137. An exposure of a ground-moraine sheet left by the great glacier of the Ice Age. Fifteen miles east of North Bay, Ontario, Canada.

ridge of irregular hills extending the whole length of the Island. This morainic ridge dominates the topography of the Island.

If, after a glacier has retreated a considerable distance, its terminus again remains relatively stationary for some time, another terminal deposit will accumulate around it. Such a deposit (*recessional moraine*) develops during every considerable pause in the recession of a glacier. Recessional moraines, forming a great succession of curving ridges, are wonderfully displayed to the south of Lakes Michigan and Erie. These mark successive pauses of the waning Labradorean ice sheet of the Ice Age.

*Lateral Moraines.* When a glacier melts, a *lateral moraine*, formed alongside the living glacier, may be left in the form of a more or less conspicuous ridge.

*Drumlins.* These are unstratified glacial deposits of unusual interest. They represent, in reality, only a special form of ground morainic ma-

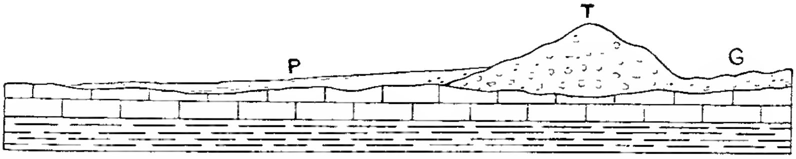



FIG. 138. A structure section showing several kinds of glacial deposits resting upon bedrock. Ground moraine, G; terminal moraine, T; and outwash plain, P.

terial (Fig. 139). They are typically low, rounded mounds or hills of till with elliptical bases; long axes parallel to the direction of the glacier movement; and steepest slopes facing the direction from which the ice flowed. They are commonly from 50 to 200 feet high, and one-

FIG. 139. Typical drumlins (side view) in western New York. (Photo by H. L. Fairchild.)

fourth to one-half of a mile long. One of the grandest displays of drumlins in the world is in the general region between Syracuse and Rochester, New York, where thousands of them rise conspicuously above the level of the Ontario Plain (Fig. 139). Drumlins are abundant in eastern Wisconsin, and in a part of Ireland. Some also occur in the Connecticut Valley of Massachusetts, and around Boston.

The mode of origin of drumlins has not been precisely determined, but it is known that they form near the margins of broad lobes of glacial ice probably either by ice erosion and rounding-off of till, or by accumulation of till beneath the ice under peculiarly favorable conditions, as perhaps in longitudinal crevasses.

*Erratics.* These are glacial boulders left strewn irregularly over the country during the melting of the ice. They vary in size from pebbles to masses as big as small houses. Most of them consist of hard rock, because the softer materials are generally ground up soon by the action of the glacier. Some erratics have been moved but short distances from their parent ledges; many have been transported at least a few miles; while some have been carried hundreds of miles. Thus boulders of Adirondack Mountain rocks occur in southern New York, and certain erratics in southern Minnesota came from ledges well up in Canada. Erratics are extremely abundant in New England and New York where much land had to be cleared of them before it could be cultivated. They occur even high up on the mountains. The author has observed erratics of sandstone, derived from ledges in the St. Lawrence Valley a few hundred feet above sea level, on the tops of mountains 4000 feet high. Erratics weighing from 5 to 20 tons have sometimes been left in such remarkably balanced positions on bedrock that they can be made to swing back and forth slightly by pressure of the hand. Such boulders are sometimes called "rocking stones." The author recently observed a large erratic standing on edge at the very summit of a peak 2600 feet above sea level in northern New York. Still another case observed by the author was a rounded erratic

FIG. 140. A big glacial boulder remarkably perched upon another boulder. East of Blue Ridge P. O., New York.

about 14 feet in diameter remarkably balanced on top of another rounded erratic of about the same size (Fig. 140).

**Fluvio-glacial Deposits.** *Valley trains.* Waters emerging from the ice are usually heavily loaded with rock débris. When such waters flow down a valley which slopes gently downward away from the end of a glacier, the tendency is to deposit some or most of the load on the valley floor, often for miles beyond the ice front, forming a valley train (Fig. 141). Deposits of this kind, somewhat cut away by post-Glacial erosion, are finely exhibited in most of the gently southward sloping

FIG. 141. A broad valley train being formed by a braided stream emerging from a glacier. Hidden Glacier, Alaska. (After Gilbert, U. S. Geological Survey.)

valleys of southwestern New York. Valley trains are of course stratified.

*Outwash Plains.* When the front of a great glacier pauses for a considerable time upon a rather flat surface, the débris-laden waters emerging from the ice spread in a network of streams and deposit the débris more or less uniformly over the surface, forming an *outwash plain* (sometimes called a *frontal apron*) (Fig. 138). A very fine illustration is most of the southern half of Long Island lying just south of the great terminal moraine. Outwash plains are of course stratified. They are seldom formed by ordinary valley glaciers.

Depressions from 10 to 100 feet deep, with no outlets and with steep sides, are often formed in outwash plains. These so-called *kettle holes* result from melting of blocks of ice which become separated from the glacier during its retreat and buried under the outwash material. Kettle holes may also develop in glacial lake deposits where icebergs become stranded, buried under sediment, and subsequently melted. Some of the depressions in terminal and recessional moraines, and also in groups of kames, are kettle holes.

*Kames.* These are hills of stratified glacial débris with rounded outlines commonly from 50 to 150 feet high. They may exist as isolated hills or in small groups (Fig. 142), or they may be associated with

FIG. 142. Kame hills, five miles west of Gloversville, New York.

unstratified deposits of moraines. When they are grouped, deep depressions occur between the hills, giving rise to what is called "knob and kettle" topography. They occur most generally in valley bottoms, but sometimes on hillsides, or even on hilltops. They are rather common and widely distributed over the great glaciated region of the northern United States, particularly in association with terminal and recessional moraines. Sometimes they form so-called "kame-moraine" ridges. Kames form at the margins of glaciers by débris-laden streams which heap up the material (usually sand and gravel) as they emerge from the ice. Sometimes the débris-charged water rises as great fountains. Kames are now actually in process of construction alongside some of the great Alaskan glaciers.

*Eskers.* These are long, usually winding, low ridges of stratified glacial material, consisting mainly of sand and gravel. They are seldom over 75 to 100 feet high, and their crests are generally narrow and rather even (Fig. 143). They are usually less than a mile long, but

FIG. 143. Part of an esker, showing its winding course. North Creek, New York.

in Scandinavia and elsewhere individual eskers have been traced many miles. They often look like artificial railway embankments. They were formed by deposition in streams, choked (or overloaded) with glacial débris, either in channels on glaciers, or in tunnels beneath the ice.

# CHAPTER IX

## GEOLOGICAL ACTION OF WIND

### Importance of Wind Work

Wind is an important geological agent of erosion and transportation of rock material, but is not as effective as running water. It is in arid and semi-arid regions that the wind is most effective as a geological agent. The importance of wind work becomes impressive when we realize that desert conditions prevail over about one-fifth of all the lands of the earth. In deserts weathering effects requiring moisture in the air are reduced to a minimum; stream action is in general much less important as a factor of erosion and deposition than in humid regions; and frost action, due to lack of water, is relatively unimportant. The temperature changes in deserts are, however, exceptionally great and rapid, as between night and day, and so the rocks, which are nearly everywhere directly exposed because free from vegetation, are broken up relatively fast as a result of repeated and rapid expansion and contraction.

Winds not only erode, transport, and deposit rock materials, but they also stir up waves and shore currents which in turn become effective and important geologic agents, as discussed in Chapter X.

### Transportation by Wind

It is as an agent of transportation that wind accomplishes its greatest work. Corrasion by wind action cannot proceed without transportation of loosened materials, but tremendous quantities of rock materials, already loosened and subdivided by processes other than corrasion by the wind, are transported by the latter.

What are some of the sources of the finely divided rock material which is transported by winds? Most of the material by far is picked up from dry surfaces of loose, fine materials of all kinds in all sorts of regions, but especially in deserts where such materials are blown about by every wind. Some of it is directly derived from rock ledges by the erosive action of the wind itself, as explained beyond. Considerable quantities of dust are contributed to the atmosphere by explosive

eruptions by volcanoes whereby lava is pulverized and shot far into the air (Fig. 174). During the explosions of Krakatoa, East Indies, a tremendous quantity of finely divided and pulverized rock was forced miles into the air, and some of it was carried completely around the earth and remained suspended for many days, causing the famous red sunsets of 1883. Several cubic miles of volcanic dust were forced out of Katmai Volcano, Alaska, in 1912 when the mountain exploded. This dust caused darkness for many miles around for more than two days; and at a distance of 100 miles it accumulated to a depth of 10 inches.

The almost inconceivable transporting power of strong winds over deserts is illustrated by the well-known "sandstorms" of the Sahara Desert. In such a great storm many cubic miles of dust and sand-laden air sweep miles across the country. It has been estimated that one cubic mile of air in such a storm carries at least 100,000 tons of rock material. Dust from the Sahara is known to be carried hundreds of miles out into the Atlantic Ocean. According to an estimate, a great storm in 1901 carried nearly 2,000,000 tons of finely divided rock material from northern Africa into Europe. In two days some of the dust fell in Italy and in three days some of it reached central Germany.

## Wind Erosion

Wind picks up and carries along great quantities of dry, loose, finely divided material, but of itself it has little or no power to erode solid rocks. Wind, like water, effectively erodes rocks when properly supplied with tools, that is, when it has rock fragments with which to work. When fine material, especially grains of sand, are driven by wind with high velocity against barren rocks, the latter are worn (corraded) and often polished by the process. The principle involved is that of the sand blast used in cleaning and polishing decorative and building stones, and in etching glass. Where rock ledges show many local variations in composition and hardness, they are often etched by wind erosion into very irregular, and often fantastic, forms.

A surprising amount of erosion may be accomplished by the wind, under very favorable conditions, in a short time. A plate glass window in a Cape Cod lighthouse is said to have been worn to opaqueness during a single hard wind storm. Window glass directly exposed to hard winds on Cape Cod is known to have been completely worn through within a few weeks or months.

Wind-driven sand has its greatest erosive power relatively close to the ground because the heavier and larger fragments, not being lifted so high, there accomplish the greatest work. Telegraph poles

FIG. 144. A striking example of rock forms scoured and sculptured by wind corrasion. At times loose sand is picked up from the bottom and driven at high velocity through this troughlike depression. Rogers Dry Lake, Mohave Desert, California. (Photo by E. Blackwelder.)

in desert regions often must be especially protected else they will be cut down by sand driven against their bases. Pebbles and boulders on deserts sometimes have more or less angular faces carved upon them by wind erosion, and rock platforms are often kept worn smooth and hard.

## WIND AND STREAM EROSION COMPARED

Careful observations during the last ten to twenty years have led to the conclusion that the corrasive action of wind is much less generally effective in sculpturing and cutting away rocks than formerly surmised. There is, however, no doubt about the local efficacy of wind corrasion when conditions are very favorable (Fig. 144).

Stream erosion, even in desert regions, accomplishes much more work than wind erosion because when it rains it is often in the form of so-called "cloudbursts." In desert areas of high relief, therefore, torrents of water rush down the stream courses carrying heavy loads of rock débris derived from the abundant weathered rock material almost unprotected by vegetation. The deep sculpturing of the desert mountains

of Nevada, Arizona, western Utah, and eastern California is very largely due to water, and not wind, erosion.

The author has observed thousands of well exposed outcrops in the vast western desert showing plain evidence of mechanical and chemical weathering, but with little or no evidence of wind corrasion.

The greatest geologic work accomplished by the wind seems to be the picking up and transporting of really large quantities of finer materials which either were laid down through the agency of running water or were produced by weathering. Such action of the wind is called *deflation.*

## WIND DEPOSITION

**Dunes.** Hills of wind-blown sand are called *dunes.* They are formed in much the same manner as snowdrifts. They are abundant in many regions, as for example along the middle Atlantic Coast of the United States; around the southern end of Lake Michigan in Dune

FIG. 145. A crescentic sand dune in Wyoming. (Photo by E. E. Smith, U. S. Geological Survey.)

Park, Indiana; and in the desert portions of the western United States. Dunes mostly form in deserts; on and near sandy shores of lakes or oceans where the wind blows toward the land; and on and near river flood plains, especially in arid regions where the volume of water varies greatly. Dunes seldom attain heights greater than a few hundred feet, though some in the Sahara Desert are said to be more than 1000 feet high.

A dune may begin to build up where there is a slight irregularity

of surface, or some obstacle such as a boulder, causing a local check in the velocity of the wind with resultant deposition of some of the load it carries. Once the pile has started, its growth is accelerated by its own shape and size. Where the direction of the wind remains fairly constant, the tendency is for a gentle slope to develop on the windward side, and a steep slope on the lee side. Sand blown up to the crest of the windward side is caught in a relative calm with a back-eddy on the lee side of the hill, and there deposited. The lee side is steeper because the sand rolls down its slope (Fig. 145). Smaller

FIG. 146. A group of ripple-marked sand dunes in the Imperial Valley, California.

dunes are often somewhat crescent-shaped, caused by the wind driving sand both over and around the dune (Fig. 145). When the winds are rather variable in direction the sand dunes are more irregular in shape.

Dune sand is usually crudely stratified, with prominent cross-bedding, due to the varying velocity of the wind which causes alternately larger and smaller sand particles to be driven up the slopes and deposited in layers. Sand dunes are often beautifully ripple-marked on their surfaces by more or less parallel ridges an inch or more high (Fig. 146).

**Migration of Dunes.** Unless prevented by vegetation, dunes usually migrate in the direction of the prevailing wind. The migration

is caused by the blowing of the sand up the windward slope, and its deposition on the steeper leeward slope. On a dry, windy day the sand can be seen blowing over the crest of a dune. The rate of migration is of course determined by several factors. Most dunes migrate at rates of from a few feet to more than 100 feet per year. A case of unusually rapid movement was that at Kunzen on the Baltic Coast where a large dune encroached upon, buried, and then uncovered a church, migrating about eight miles between the years 1809 and 1869. A pine forest, covering hundreds of acres on the coast of Prussia, was destroyed by migration of dunes between 1804 and 1827. In many places portions of farms have been ruined by migration of dunes within the lifetime of single owners. Forest trees have, in many places, been buried, killed, and then uncovered by drifting sand. Such phenomena are well exhibited in Dune Park, Indiana.

**Removal and Deposition over General Areas.** Wind-blown material does not, by any means, always accumulate in the form of dunes and ridges. Wind action often tends to level off large areas by removing loose materials from higher lands and depositing them in intervening depressions, or piling them against bases of mountains. This is true on a grand scale in portions of the Sahara Desert where certain wide areas of bedrock are kept free from sand by wind erosion, and the sand is piled against the mountain bases, and even up the slopes to heights of 1000 to 2000 feet. In the Great Basin region of the western United States somewhat similar phenomena are not uncommon.

FIG. 147. A sand dune advancing upon a forest. Near Port Burwell, Ontario.

The ruins of the once great cities of Nineveh and Babylon are largely buried under wind-blown sand and dust. Evidence has been presented to show that the climate of western and central Asia is now considerably drier than it was a few thousand years ago. This helps us to understand why so many old villages and cities there have been buried under wind-blown deposits.

**Loess.** A kind of deposit of special interest, which is mainly or partly of wind-blown origin, is called *loess*. It is usually a fine-grained unstratified, yellow to brown loam or silt which, though very slightly consolidated, has the remarkable property of standing in the form of high, very steep slopes or cliffs where it has been cut into by erosion (Fig. 148). It sometimes contains shells of land animals. It forms extensive deposits, commonly from 10 to several hundred feet thick, in various regions.

Certain valleys of northern Europe, especially the Rhine, contain loess deposits. Extensive deposits occur in Argentina. Thousands of

FIG. 148. A roadway through a deposit of loess in China. Note the vertical structure. (Photo by Bailey Willis.)

square miles in Iowa, Nebraska, and Kansas (particularly in the Missouri and Mississippi Valleys) are covered with loess which is seldom more than 100 feet thick. This is believed to represent the fine loose material blown by the wind from the adjacent regions just after the withdrawal of one of the great glaciers of the Ice Age. The loose glacial soils were then protected by little or no vegetation. Many thousands of square miles of northern China are covered with loess, much of which may have been blown from the Mongolian desert. It covers both mountainsides and valleys to depths probably as great as 1000 feet. Some of this loess has probably been reworked and deposited by water.

# CHAPTER X

## THE SEA AND ITS WORK

### Definitions

According to good general usage the terms *sea* and *ocean* are practically synonymous and refer to the whole continuous body of salt water, including its numerous embayments, which covers a large part of the earth's surface. The term *sea* is preferred in this book. Such names as the "Sea of Galilee" or the "Dead Sea" are misnomers because, being inland bodies of water (one salt and the other fresh) not connected with the great general body of salt water, they are really lakes.

Certain scientific distinctions of use to oceanographers, geographers, and geologists, may be made as follows. The *oceans* are very large bodies of deep-sea water occupying basins between continents. Thus we have the Atlantic, Pacific, Indian, Arctic, and Antarctic Oceans whose average depth is about two and a half miles.

*Epicontinental seas,* seldom over 600 feet deep, occupy the narrow platforms (continental shelves) which border the lands nearly everywhere. They are, in other words, shallow-water, landward extensions of the open ocean. They are also known as *shelf* or *marginal seas.* A fine example is the sea covering the continental shelf off the eastern United States. Other examples, less open to the ocean, are the North Sea, the Yellow Sea, and the Gulf of St. Lawrence.

*Epeiric seas* are also shallow (seldom over 600 feet), but they lie well within continental regions and their connection with the ocean is less open. Probably the finest example is Hudson Bay. The Baltic Sea, extending northward into the Gulf of Bothnia, is another good example. During the geologic ages, particularly the Paleozoic era, it was epeiric seas which repeatedly spread over, and withdrew from, large and small parts of continents. Most of the exposed marine strata of North America and Europe were deposited in epeiric seas.

A *mediterranean* is a special type of sea much like an epeiric sea, but it has depths of thousands of feet. The Mediterranean Sea is the finest example, and the Caribbean Sea may be classed in this category.

## Geological Importance of the Sea

The deep seas, such as the Atlantic and Pacific Oceans, are geologically very old, and they have probably remained in essentially the same positions for hundreds of millions of years. Shallow seas have, however, as already mentioned, spread over, and disappeared from, large and small parts of continents time and again during the geologic eons. It is plain, as shown by the character and origin of the marine strata now exposed on the lands, that no deep sea (true ocean) ever spread over any considerable part of a submerged continent.

The sea is now, and has been through known geologic time, the greatest theater of sedimentation. Shallow-water marine strata of practically all known ages are very extensively exposed within the continents. Such strata have been piled up to a total thickness often reaching 5 to 15 miles. In many cases they have been greatly disturbed (folded and faulted) out of their original position and deeply eroded, thus exposing to view the records which they contain. Had it not been for the accumulation of these marine strata, far less would be known about many of the great and small physical changes through which the earth has passed.

Marine strata also contain countless myriads of remains and impressions of animals and plants (i.e. fossils), and thus we have a very important key to a knowledge of the kinds, distribution, and history and evolution of life on the earth through hundreds of millions of years.

The sea has, through the long ages, been incessantly at work cutting into and modifying many parts of the bordering lands.

The climatic influence of the sea has also been of real importance. Thus the moisture in the air, rain which forms streams, and snow which forms glaciers, have their sources very largely in the ocean, and these agents in turn accomplish great work of weathering and erosion.

## Extent and Depth of the Sea

It is well known that the waters of the sea cover nearly three-fourths of the surface of the earth. The sea is about 45 times as large as the United States, that is, it covers approximately 140,000,000 square miles. The average depth of the oceans of the earth is about two and a half miles. If the sea were present universally, everywhere with the same depth, it would be almost two miles deep. Yet this vast body of water is an extremely thin layer when compared to the earth's diameter of nearly 8000 miles.

The Pacific is the deepest of the oceans, its average depth being about two and three-quarters miles. The deepest sounding ever made was 35,410 feet, or more than six miles, off the southern Philippine Islands. It is known as the *Mindanao deep*. The second greatest depth known is 34,623 feet, in the *Tuscarora deep*, off southern Japan. There are many places in the Pacific Ocean where the water is four to five miles deep. The deepest sounding ever made in the Atlantic Ocean was nearly 28,000 feet, off Puerto Rico.

## Topography of the Sea Floor

If we make a general comparison with the surface of the land, the bottom of the sea, well out from the land, is generally the smoother. Little of the sea bottom compares with the ruggedness of the mountains, and even the more level portions of the land surface nearly always show many sharp, minor irregularities, such as stream trenches; but the sea bottom is characterized more by its smoothness of surface. Under the sea there are, however, mountain-like ridges, plateaus, submarine volcanoes, and valleys, the deeper valleys being known as *deeps*, but such features, 100 miles or more from the shore, seldom show roughness of relief such as characterizes similar features on land.

One of the most remarkable relief features of the ocean bottom is the so-called *continental shelf*. It is a relatively narrow platform covered by shallow water bordering nearly all the important lands of the earth. Usually the water increases in depth seaward over this platform, but it seldom exceeds a depth of more than 600 feet. The continental shelves of the world cover about 10,000,000 square miles, or about one-fourteenth of the area of the sea floor. "The break in the slope at the outer margin of the continental shelves is found at depths of approximately 400 feet off most of the coasts of the world. It seems probable that this uniformity was developed by the cutting of the waves at a time when the sea level was much lower than at the present time. Such a lowering did occur at the time when the sea water was extracted from the ocean and piled up on parts of the land to form the great continental glaciers of the past" (Shepard).

On the way from New York to Europe, a ship sails over the continental shelf for about 100 miles, the water gradually increasing in depth to about 600 feet. Then there is a comparatively steep descent (called the *continental slope*) into the great *ocean abyss* which is two to three miles deep. The floor of this abyss, stretching across the

Atlantic almost to the shores of Europe, is generally lacking in sharp topographic changes. A little more than half way across, the ocean bottom rises as a kind of submarine plateau or ridge a few hundred miles wide, with water not more than one to two miles deep over it. This submarine ridge runs roughly north and south with a winding course through nearly the whole Atlantic Ocean. Within a few hundred miles of Europe the sea bottom begins to rise on a continental slope to a continental shelf which, with its shallow water, extends to the shore.

## Marine Erosion

**How Waves Erode.** When a wave dashes against a rocky shore or cliff, water is forced into many cracks and other openings, causing a hydraulic pressure which tends to disrupt blocks of rock in the face of the cliff. Also many fissures and crevices are suddenly filled with compressed air which, on retreat of the wave, has its pressure relieved quickly, thus producing a so-called "suction" which often dislodges

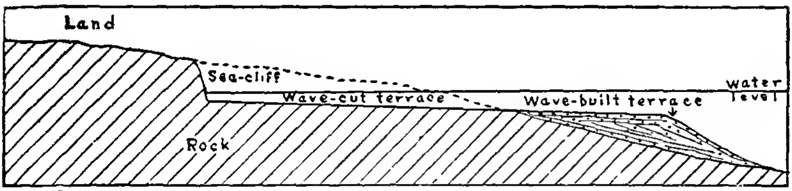



Fig. 149. Diagrammatic structure section illustrating the development of the sea cliff, wave-cut terrace, and wave-built terrace.

masses of rock. The very impact of the wave against a shore may be sufficient to force off rock material from a cliff, not only of soft or loose rock, but also of hard rock if there are masses of it already sufficiently loosened by jointing or weathering. A minor factor in the removal of rock material by waves is the solvent action of sea water.

Waves are most effective as agents of erosion through their grinding action. Waves, like running water, wind, and glaciers, erode most effectively when properly supplied with rock fragments as tools with which to work. When strong waves, armed with rock fragments already dislodged from the shore, repeatedly strike a rocky shore or cliff, they become powerful agents of shore destruction. Even the hardest rocks must yield to such abrasive (or corrasive) action. Such battering of the rock fragments of all sizes, and their rubbing against one another

when carried by the undertow, soon cause the fragments to become rounded (Fig. 150). The older fragments are worn down from pebbles and boulders to fine sand and mud, while new fragments are being derived from the shore. In high latitudes, when shore ice, containing many rock fragments, breaks up and is driven against the shore by wind and storm waves, it becomes an important factor of erosion.

**Sea Cliff and Wave-cut Terrace.** Where waves are at work cutting into a shore of at least moderately high land, a steep front facing the sea soon develops. This is called the *sea cliff*. At first

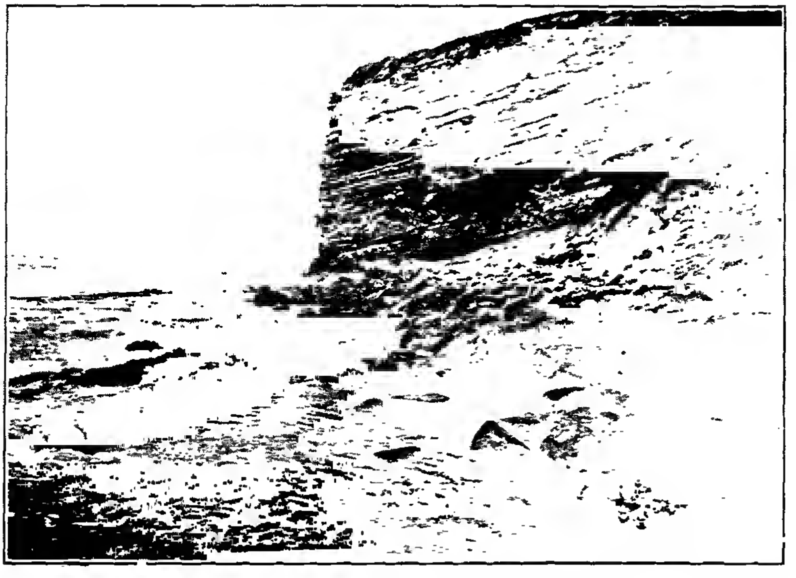


FIG. 150. Sea cliff with wave-worn boulders at its base. Near San Pedro, California.

the waves may attack the whole face of the cliff, but after a time the cliff becomes so high that the waves attack only its lower portion. By this undercutting process, aided by weathering, the material from the higher portion of the cliff breaks away and falls to the base to furnish more tools with which the waves may batter the cliff. It is by the process just outlined that the sea cuts its way horizontally into the land.

As the sea cliff retreats, a shallow-water shelf, called the *wave-cut terrace* (Fig. 149) develops, over which the water increases in depth seaward to the limit of wave action, that is, to a depth of hundreds of feet. Such a terrace will not, as a rule, be cut many miles wide because

the waves, in moving over the shallow-water shelf, lose their power gradually on account of friction on the bottom. With a slow sinking of the coast, a much wider wave-cut terrace may of course be produced by wave erosion.

Much material cut away and ground up by the waves is carried seaward usually to build up the *wave-built terrace* (Fig. 149), which is something like a submarine delta. Some of it is carried by shore currents to form spits, bars, etc., as explained beyond. Observations during the last decade have led to the conclusion that large, well-defined

FIG. 151. Sea waves eroding a rocky coast. Santa Cruz, California.

wave-built terraces are by no means as common as was once supposed. This matter is discussed more fully beyond under the caption "Marine Deposits."

**Rate of Retreat of Sea Cliffs.** The rate of retreat of sea cliffs is known in many places. The rate is of course dependent upon various factors, particularly the force and persistence of wave action, and the nature of the rocks attacked. A cliff of loose material is often cut back so rapidly as to be a matter of common knowledge. A remarkable example is the island of Heligoland on which, until recently, was located the powerful German fort, guarding the Kiel Canal. In the year 800 A.D., this island had 120 miles of shoreline; in 1300 it had 45

miles of shore; in 1649 only eight miles; and in 1900 only three miles.

In southeastern England "whole farms and villages have been washed away in the last few centuries, the sea cliffs retreating from 7 to 15 feet a year." A church located a mile from the sea-shore near the mouth of the Thames in the 16th century now stands on a cliff overlooking the sea.

An island of soft-rock material in Chesapeake Bay covered over 400 acres in 1848, and the waves reduced it to about 50 acres by 1910.

Certain cliffs of soft material on the island of Martha's Vineyard

FIG. 152. Remnants of wave erosion (so-called "stacks"). La Jolla, California.

retreated five and one-half feet per year between 1846 and 1886. Wave erosion on very hard rock, like granite, is far less rapid.

**Sea Caves, Coves, Stacks, and Arches.** Many irregularities are often developed during the retreat of the sea cliff and the cutting of the wave-cut terrace. *Sea caves* are often produced along the bases of cliffs by wave action, especially where masses of weaker rocks lie at or near sea level.

If, along a coast, masses of more easily eroded rocks are separated by harder or more difficultly eroded rocks, the waves will cut the former back faster to form *sea coves,* while the latter project into the sea to form *headlands.*

If part of the roof of a sea cave collapses, or if two caves on opposite sides of a sharp headland unite, a *sea arch* results (Fig. 153). The waves will continue to batter the arch until it collapses.

Unequal wave erosion along a rocky coast often leaves isolated portions of cliffs known as *stacks* (Fig. 152). They are at most very temporary objects. A famous example is the Old Man of Hoy in the Orkney Islands. It is an isolated joint column of colored sandstone 600 feet high. Many examples of stacks occur on the New England coast, and on the Pacific coast of North America.

FIG. 153. A natural bridge carved out by high-tide waves. Santa Cruz, California.

**Plains of Marine Erosion.** With sufficient uplift of land relative to sea level, a wave-cut terrace becomes a *plain (or terrace) of marine erosion*. The surface of such a plain, like that of a stream-developed peneplain, cuts across all kinds of rocks irrespective of their composition and structure. On a peneplain, however, the rock waste is characteristically a residual soil, while that of a plain or marine erosion consists of water-worn transported material rather uniformly spread over the surface. The surface of a newly upraised marine plain is usually smoother than that of a plain of stream erosion, and the erosion remnants left by the waves are steeper sided than those on a peneplain formed by streams. A remarkable example of a long plain of marine erosion

with steep-sided, isolated masses (former islands) rising above its surface occurs on the eastern side of India.

A conspicuous marine terrace, usually with an altitude of approxi-

FIG. 154. A marine terrace (with "stack") being cut into by sea waves. Near Pismo, California.

mately 100 feet, faces the sea at many places along several hundred miles of the coast of southern California (Fig. 154). Still higher terraces, proving successive uplifts of the sea floor, are also well preserved along parts of this coast.

## MARINE DEPOSITS

Viewed in a broad way, there are two great classes of marine deposits: (1) those laid down in shallow water comparatively near the borders of the land, that is, on the continental shelf and continental slope; and (2) the abysmal (deep sea) deposits laid down on the floor of the deep ocean.

**Shallow-water Deposits.** *General statement.* Marine sediments which accumulate along and near the continental borders are largely land-derived materials, that is, they are mostly sediments carried by streams from the land into the sea, and to a less extent rock materials broken up by the waves along many shores. Practically all land-derived material is deposited within 100 to 300 miles of the shore. The quantity of such sediment carried into the sea each year is tremendous. Thus the Mississippi River carries several hundred million tons of sediment into the Gulf of Mexico each year.

The continental border deposits are extremely variable. Near the shore they are chiefly gravels and sands, while farther out they gradually become finer, and on the continental slopes only muds are deposited. Recent investigations have, however, shown that such a gradation outward from coarser to finer material is, by no means, as common as formerly supposed. These deposits usually contain more or less organic material, especially shells and skeletons of organisms. In some cases such organic remains predominate, or even exist to the exclusion of

Fig. 155. A crescentic gravel beach. Conception Bay, Newfoundland. (Photo by C. D. Walcott for U. S. Geological Survey.)

nearly all other material, as is true of the coral deposits (or reefs) which form only in warm, shallow water.

*Beaches and barriers.* The loose material, ranging in size from very fine to large boulders, which is shifted and ground up by the action of the waves, undertow, and shore currents, is called the *beach*. It consists of the zone of rock fragments within reach of the waves along the shore. "Its lower margin is beneath the water, a little beyond the line where the great storm waves break. Its upper margin (on shore) is at the level reached by storm waves, and is usually a few feet above still water" (Chamberlin and Salisbury). The upper portion of the beach consists generally of coarser material, while its lower, or constantly under-water portion, is made up of finer material. Beaches are, as a rule, not prominently developed at the bases of sea cliffs, but (except along very young coasts) they are well-developed generally around the

shores of coves and recesses of the coasts (Fig. 155). Where the land slopes down to the sea gently, as on coastal plains, beaches are often also finely developed.

Where the sea bottom slopes very gently from the shore, materials which are derived by inflow of streams, and spread over the bottom by currents and undertow, may be acted upon by waves which drag the bottom and break some distance from the shore. The breaking of such waves causes the water (not merely the wave form) to rush forward, stirring up and dragging along sediment. The undertow carries back

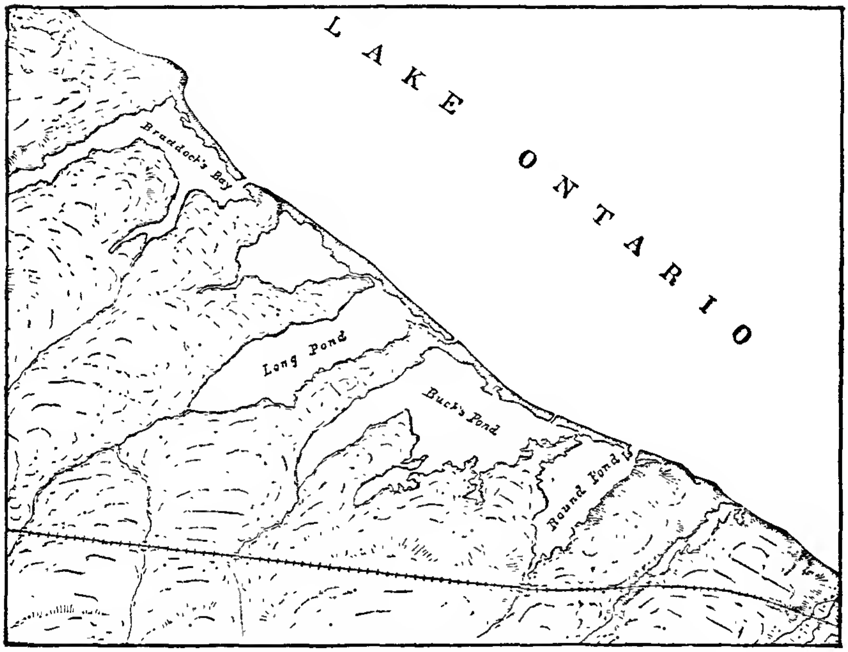



FIG. 156. Map showing bars almost completely enclosing embayments of Lake Ontario. (After U. S. Geological Survey.)

much of the material which tends to accumulate in an offshore zone where the forward rush, and the reversed undertow movement, about counterbalance. A long *barrier beach*, or a series of *barrier islands*, thus builds up some distance out, parallel to the general coastline (Fig. 158). It may be built up to the surface of the water by wave action, then increased in height by wind action, forming sand into dunes. Such barrier beaches are prominent along the Atlantic and Gulf coasts from New Jersey to southern Texas.

The water of the area between the barrier and the shore is called a *lagoon* or sound, depending upon its size. Its water is seldom more than 10 or 20 feet deep. Lagoons are often converted partly into

marshes either by accumulation of sediment from the land, or by vegetation, or by both. Atlantic City, New Jersey, is built upon a barrier beach bordering such a lagoon.

*Spits and bars.* When a shore current carrying sediment, comes to a cove or a narrow embayment on the coast, it tends to keep to its course rather than to follow the shore of the embayment. The sediment-

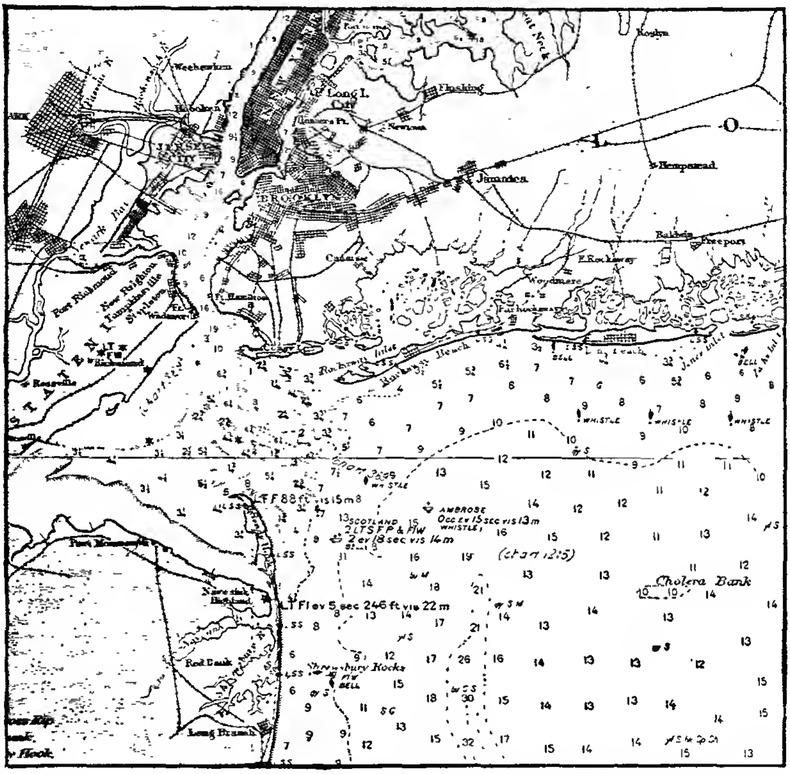



FIG. 157. Map showing beaches and spits near New York City in 1916. Figures represent depths in fathoms below low tide. (After U. S. Coast and Geodetic Survey.)

laden shore current thus moves into deeper, quieter water where its load is deposited, and thus a *spit* builds out from the shore (Fig. 156). When the current moves across the mouth of an embayment, the spit may continue to extend until it nearly, or quite, closes the embayment. It is then called a *bar* (Fig. 160).

*Deltas.* The building of deltas, often of large extent, into the sea

(or into lakes) by rivers, under certain conditions, has already been considered in the discussion of stream deposition in Chapter VII. Sea deltas are built of land-derived materials carried in by rivers, but they may be regarded, in a real sense, as marine deposits because they build out into the sea.

*Wave-built terrace.* Where sea cliff and wave-cut terrace are both being eroded by wave action, the loosened materials are ground up and, in large part, may be gradually shifted over the bottom to the deeper water at the seaward edge of the wave-cut terrace, and there deposited. A very considerable *wave-built terrace* may be formed by this process in the course of time (Fig. 149). The continental shelf is often a combination of wave-cut and wave-built terraces. Recent investigations have, however, shown that, in a surprising number of cases, wave-built terraces are not formed, but, instead, the sediments move down the continental slopes into deep water.

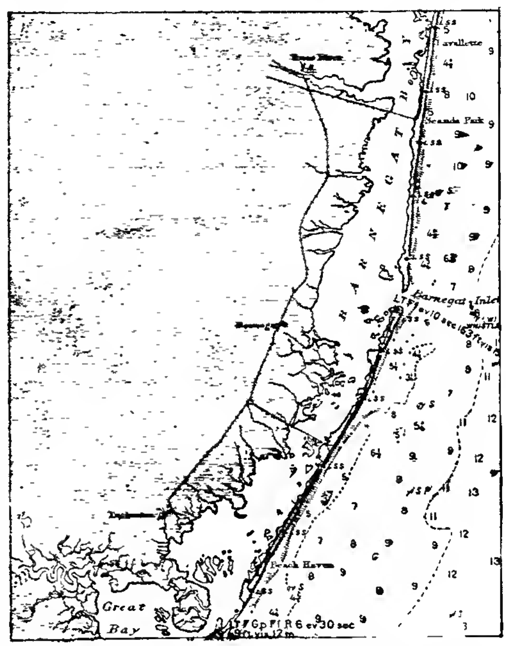



Fig. 158. Barrier beaches along the New Jersey coast in 1916. Depths in fathoms below low tide. (After U. S. Coast and Geodetic Survey.)

Shallow-water features, such as sea cliff, wave-cut terrace, beach, barrier, bar, and spit, are often preserved for some time after elevation of the shallow-sea bottom into land.

**Deep-sea Deposits.** The deposits on the deep-sea bottom, down to depths of two and three miles, are very largely organic, that is, mainly shells and other remains of organisms which have fallen to the bottom from near the surface of the sea as already explained. The most common of such deposits are the deep-sea ***oozes*** which are made up of the remains and shells of tiny animals and plants. Such oozes cover about 60,000,000 square miles of the deep-sea bottom.

At depths greater than two to three miles, a peculiar red clay is the primary deposit. It is very widely distributed, covering an area of 55,000,000 square miles, or an area as large as all the lands of the

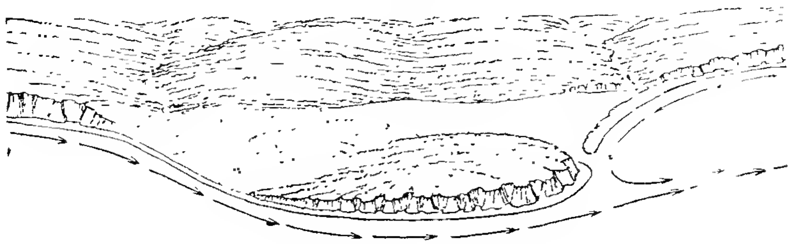


FIG. 159. A diagram to show how a bar may be built across a bay, by an eddy, in a general direction opposite to that of the main shore current. Arrows indicate directions of currents. The long bar almost completely enclosing San Diego Bay, California, excellently illustrates this principle. (After W. M. Davis.)

earth. Some remains of organisms are mixed with the clay, but since most of the shells are limy and very thin, they are dissolved without

FIG. 160. A fine example of a bar built across an embayment. Coast of California, near Crescent City. (Photo by W. G. Johnson.)

reaching the bottom in the very deep water which is not only under great pressure, but also rich in carbonic acid gas.

The deep-sea deposits, both oozes and red clay, do, however, contain some land-derived and other materials. Thus off the west coast of Africa some dust from the Sahara Desert is known to fall into the deep sea. Volcanic dust is often carried many miles, and deposited in the deep sea, particularly in the southern Pacific Ocean. Bits of porous volcanic rock called *pumice* sometimes float long distances on the ocean before becoming sufficiently water-soaked to sink. Icebergs often drift far out from the polar regions over the sea, and, on melting, the rock débris which they carry is dropped to the sea bottom. Also particles of iron and dust from meteorites ("shooting stars") have been dredged from the deep sea.

## Normal Cycles of Shoreline Development

**Cycle Inaugurated by Submergence.** If a portion of a relatively rugged (mature) land surface is submerged under the sea, a very irregular, deeply indented or embayed shoreline results because of the entrance of tidewater into the valleys. Usually some islands are left opposite the headlands. Such drowned valleys are *estuaries*, or, if they are deep and narrow as a result of glacial erosion, they are *fiords*. Chesapeake Bay and Delaware Bay are good examples of estuaries, and excellent fiord coasts are those of Norway and southern Alaska. In the following discussion of stages in the history of such a shoreline, it is assumed that there is no movement of the land up or down to interrupt the normal cycle.

A newly formed coast of the kind just described (Fig. 161, A) is attacked by the sea waves which at first make it rougher and more irregular in detail. Then the islands are eroded away, the headlands are cut back somewhat, and sea cliffs are formed. This may be called the *youthful stage* (Fig. 161, B).

Next, a shallow-water shelf is cut by the waves, the headlands are cut back farther, bars are built across the embayments, and the latter begin to fill with sediments (Fig. 161, C).

Then the shoreline is cut back much farther, a very prominent sea cliff forms along most or all of the shore, and there is developed an extensive wave-cut shelf with sediment deposited beyond it perhaps in part as a wave-built terrace. The remaining sediment-filled embayments are now largely or wholly obliterated. This is the *mature stage* (Fig. 161, D). The waves then attack the whole rocky shore, and the shoreline develops irregularities or indentations because some

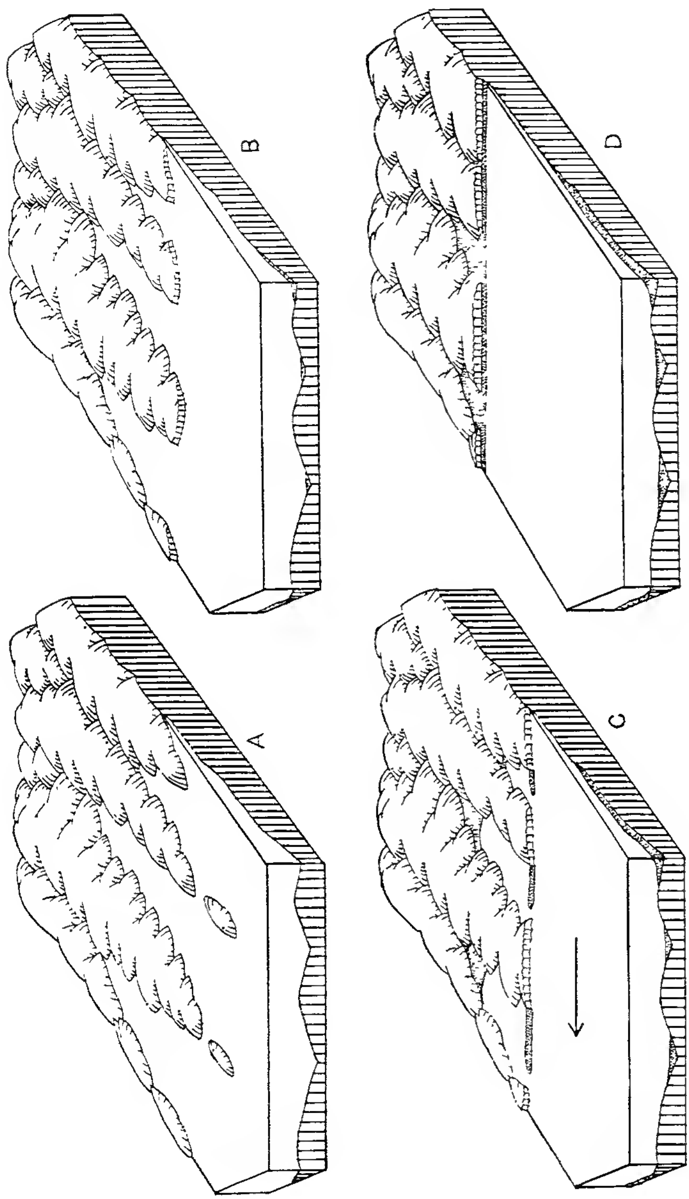



Fig. 161. Block diagrams illustrating some stages in the history of a shoreline starting with submergence of part of a mature land area. A, irregular, deeply embayed shoreline, with some islands, due to drowning of valleys; B, sea cliffs formed, headlands truncated, and islands removed; C, greater truncation of headlands, bars across the bays, and bays partly filled with land-derived sediment; and D, shoreline cut back still more, prominent and extensive sea cliffs, continuous beach, and a wide wave-cut shelf. The arrow indicates direction of shore current. (Modified after D. W. Johnson.)

(weaker) rock masses are cut back faster than others. Such indentations are, however, almost never comparable in size to those produced by the sinking of the land at the beginning of the cycle of subsidence.

In the *old-age stage* the wave-cut terrace becomes wider and wider, though at a diminishing rate because of weakened wave power on account of frictional drag where waves travel over such a wide shallow-water terrace. The sea cliff gradually becomes so faint as to scarcely merit its name any longer not only because of the weakened wave power, but also because the land is worn down to very low relief by this time. Also, because of the low land-relief, little land derived sediment comes into the sea, and so the process of clearing loose material off the wave-cut shelf is more effective than ever. There is, however, no important difference in processes involved in the mature and old-age stages.

The *final stage* is reached when the whole land mass attacked by the sea is reduced to *base level of wave erosion*, or, in other words, when a rock platform is cut everywhere to the lower (depth) limit of wave erosion, and sediments have practically all been swept off the platform. The depth of water over such a platform is usually several hundred feet, the maximum probably being about 600 feet. This final stage may be likened to the peneplain stage in the normal cycle of stream erosion.

It should be remarked that the final, or even the late old-age stage, involving a really extensive area, is largely a theoretical consideration. This is because the widening of the wave-cut shelf gradually becomes so slow, on account of steadily weakening wave power, that, long before a land mass of even much smaller than continental size is planed away, diastrophism (particularly uplift) is almost sure to interfere with the cycle.

Partial submergence of a nearly flat land area would of course inaugurate a regular, or relatively straight shoreline free from indentations. In such a case the shoreline cycle is essentially the same as that inaugurated by uplift of flat sea-bottom into land. This cycle is described under the next caption.

**Cycle Inaugurated by Emergence.** If part of relatively flat sea bottom emerges into land, the resulting shoreline is of course regular, or almost straight, and free from indentations because the line of contact between the two practically flat surfaces makes it so. In the following discussion of stages in the history of such a shoreline, it is assumed that diastrophism does not interfere with the normal cycle.

If the emergence produces a gently sloping coastal plain with very shallow water offshore for some distance, the waves, due to strong fric-

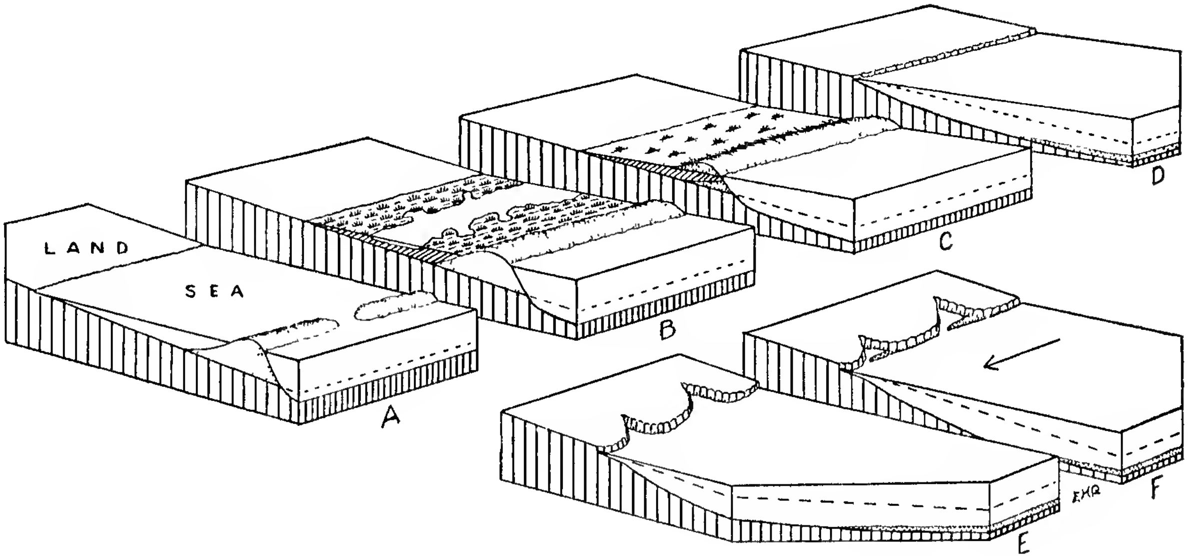



FIG. 162. Block diagrams illustrating some stages in the history of a shoreline starting with emergence of part of a flat sea-bottom into land. A, barrier beach (offshore bar) being formed; B, barrier beach completed with salt water and swamps between it and the land; C, barrier beach being eroded on the seaward side and migrating landward; D, barrier beach cut away by wave action and sea cliff formed; E, small bays cut out of weaker rocks; and F, bars formed across the bays. The arrow indicates direction of shore current. (After W. M. Davis, in part, with modifications.)

tional drag on the bottom, have practically no erosive effect upon the new shoreline. Instead, the waves, by their heavy bottom drag, transport loose materials to a zone some distance offshore where a barrier beach (or offshore bar) is built up (Fig. 162, A, B). A lagoon, usually with marshes, is thus formed between the original shore and the barrier beach. The coasts of much of Texas and New Jersey are in this stage of *youth*. The depth of water on the seaward side of the barrier beach is increased enough so that waves cut into the barrier. Some of this material, especially during storms, is carried out to sea, but some of it is carried over the barrier beach. In this way the barrier migrates toward the land, and meantime the lagoon becomes partly or wholly filled with sediment and marsh-plant remains (Fig. 162, C).

In time the barrier beach is completely removed, and the water offshore is then deep enough for the waves to attack the whole original shoreline. According to Johnson the shoreline is now mature (Fig. 162, D).

Indentations may then develop where some (weaker) rocks are cut back faster than others, but such irregularities are small (Fig. 162, E). Bars may be built across such indentations temporarily, but, during the *old-age stage* to the *final stage,* the history is practically like that of the same stages in the cycle inaugurated by partial submergence of a mature land area as described above.

Figure 162, clearly illustrating the main stages of this cycle to maturity, should be carefully studied in connection with the above statements.

In case the emergence leaves sufficiently deep water offshore, a barrier beach does not of course develop, but wave cutting starts right on the new shoreline and succeeding stages are much like those of the latter part of the cycle described in the preceding paragraph.

## Submarine Canyons

Dr. F. P. Shepard has kindly prepared the following statement for the writer:

"It has been known for almost a century that there are submarine valleys off various coasts of the world. The surveys of the sea floor in recent years have shown that these features are very numerous and of surprisingly large dimensions. Some of these are cut as deeply into the surrounding ocean floors as are the greatest of land canyons into the surrounding land surfaces. The walls of these marine canyons are as steep as the walls of land canyons. They can be traced out for many

miles from the coast and to depths of as much as 12,000 feet below sea level. Some of the most impressive of these canyons are found off the coast of California (Fig. 163).

"These valleys of the sea floor have been variously explained as the results of faulting or folding or submarine currents, but their characteristics are much more those of river cut valleys. They resemble river valleys in their sinuous courses, their dendritic tributary systems, and

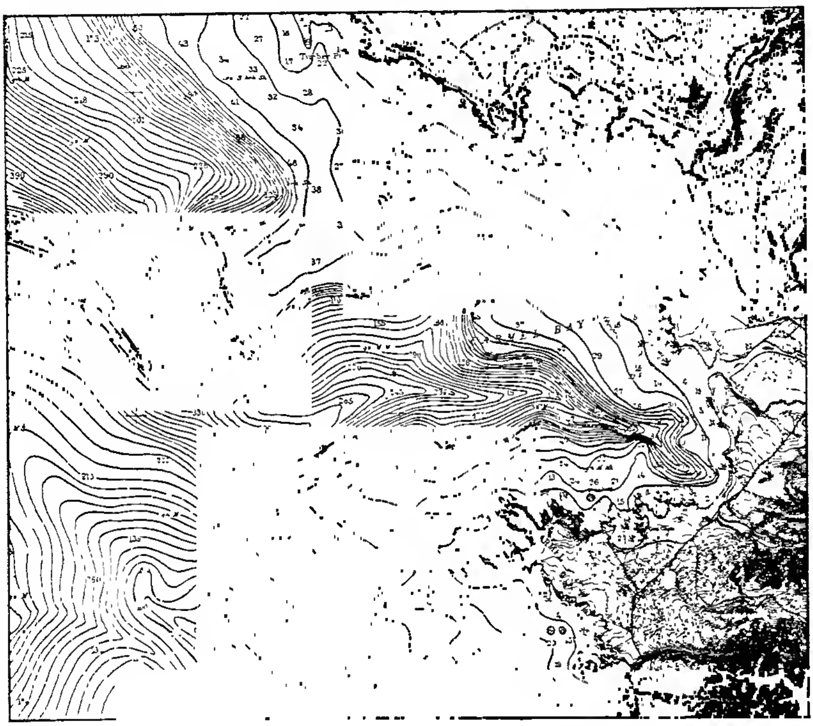


FIG. 163. The submarine canyon off the Carmel River, California. Note the dendritic pattern of the canyon. Figures show depth in fathoms. Contour interval, 10 fathoms. (After F. P. Shepard and H. H. Robinson.)

their V-shaped transverse profiles. It seems probable that they were formed at times when the coastal margins were greatly elevated (or sea level lowered) allowing streams to truncate the steep outer slopes. Subsequently submergence (or rise of sea level) carried these canyons down to the great depths at which they are now found. Since submergence, marine mud flows may have prevented the filling of the drowned canyons by the sediments washed out from the lands."

# CHAPTER XI

## VOLCANOES

### Geological Importance of Volcanoes

A volcano is a vent in the earth's crust out of which hot rocks (either molten or solid) and hot gases issue. In the popular mind, volcanoes take rank among the most important and real of all geological phenomena. This is because of both the terrifying grandeur and mighty power of violent eruptions, and their destruction of life and property. Great active volcanoes, like earthquakes, are, however, only relatively minor, outward, sensible manifestations of the tremendous earth-changing forces which operate below the surface. Volcanoes are, from the geological standpoint, much less important than the mighty interior forces which cause the rocks of the earth's crust to be folded and faulted, and large portions of continents to be upraised or depressed. Quantitatively considered, the geological work accomplished by volcanoes is notably less than the work of erosion accomplished by running water.

In our study of igneous rocks we learned that volcanic action is but one of the two important kinds of igneous activity—*plutonic* and *volcanic*—that is, deep-seated shifting and intrusion of molten materials (magmas) into the earth's crust, but not to its surface; and the eruption (or extrusion) of hot rock materials upon the earth's surface. Even as an igneous agency, volcanic action is quantitatively notably less important than plutonic (deep-seated) action.

In making comparisons like those just stated, we must bear in mind the fact that we are dealing with stupendous forces and tremendous masses of the earth's crust, so that volcanic action is, after all, not only a very conspicuous, but also a really significant, means of changing the face of the earth. The geological importance of vulcanism becomes impressive, indeed, when it is realized that, conservatively estimated, fully 500,000 cubic miles of volcanic rocks have been forced out upon the surface of the earth during the present era of geological time, and that volcanic action was important during each of the five known great eras. In some cases large mountain ranges, like the Cas-

cade Mountains of Oregon and Washington, contain great quantities of volcanic materials.

## Shapes and Sizes of Volcanoes

A volcano, in its typical form, is a cone-shaped mountain with a pitlike opening, called a *crater,* at the top, through which hot rock materials and gases are ejected. The mountain is, however, a secondary feature of a volcano. The vent is its essential part. Accumulation of volcanic rocks around the vent causes the building-up of the *cone*

Fig. 164. Molten lava seething, boiling, and swirling around an island of solid lava. Crater of Kilauea, Hawaii. (Photo by L. de Vis Norton, courtesy of the National Park Service.)

which is of course only an effect of the volcanic action. Even the great volcanoes started simply as vents or fissures in the earth's crust.

Cones of volcanic origin range in height from a few feet to several miles. Illustrative examples of well-known cones are the following: at Mono Lake, California, where there are cones only 10 to 30 feet high; Cinder Cone in Lassen Volcanic Park, California, 640 feet high; Mt. Vesuvius Italy, 3880 feet high; Stromboli, about 5000 feet high, as measured from the floor of the Mediterranean Sea on which it stands; Lassen Peak, California, and Mt. Etna, Sicily, each over 10,000 feet high; Mt. Shasta, California (Fig. 176), and Mt. Rainier, Washington, each rising to over 14,000 feet above sea level, and 8000 to 10,000 feet above the surrounding country; and Cotopaxi (altitude, 19,600

feet), Chimborazo (altitude, 20,500 feet), and Aconcagua (altitude, 23,000 feet), all of which rise 10,000 to 12,000 feet above the general level of the great elevated platform of the Andes Mountains. Very remarkable cases are Mauna Loa and Mauna Kea on the island of Hawaii, each rising nearly 14,000 feet above sea level, and fully 30,000 feet above the floor of the sea from which they have been built up.

At their bases, volcanic cones are commonly from less than a mile to many miles in diameter. Examples of a few larger ones are: Mt. Rainier, with a basal diameter of over 10 miles; Mt. Shasta, 17 miles;

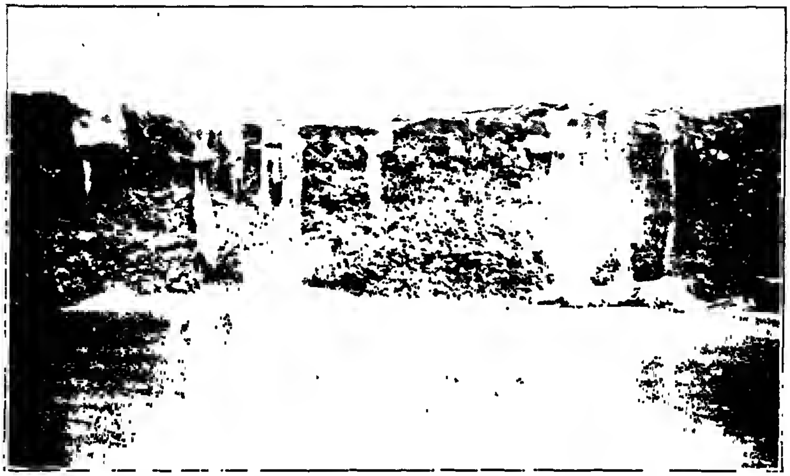


FIG. 165. Molten lava pouring over a cliff into water. Hawaii. (After Diller, U. S. Geological Survey.)

Mt. Etna, 30 miles; and Mauna Loa, with a major diameter of 74 miles, and a minor diameter of 53 miles, measured at sea level. Mauna Loa is probably the biggest volcanic cone on the earth.

Craters of active, and very recently active, volcanoes range in diameter from a few feet to several miles, and in depth from a few feet to several thousand feet. On relatively older, inactive cones, the craters have of course been partly, or completely, obliterated by erosion. Very large craters, often called *calderas*, have usually resulted either from violent explosions which have caused the tops of great cones to be blown away, or by subsidence of the mountain tops.

## Volcanic Products

**Gases and Vapors.** Tremendous volumes of gases and vapors are discharged through volcanic vents. The most abundant by far is water vapor, or steam. The quantitative importance of water vapor as a product of great volcanoes may be realized somewhat by consideration of an estimate that about 462,000,000 gallons of water in the form of steam were discharged in 100 days from a secondary cone on the side of Mt. Etna. Great clouds of steam, usually mingled with more or less volcanic dust, often rise to heights of several miles above large volcanoes during their periods of explosive activity (Fig. 174). Condensation of such steam clouds sometimes causes heavy rainfall in the vicinities of the volcanoes. Much water vapor also escapes from streams of molten lava, and the discharge often continues for weeks, or even months, after the lava solidifies.

Among the many other gases which are given off by volcanoes and lava-flows are the following: sulphide of hydrogen, oxide of sulphur, hydrochloric acid, hydrofluoric acid, boric acid, nitrogen, hydrogen, oxygen, and carbonic acid gas. All of these may not be given off during a single eruption, or from a single volcano. Some of them may not exist as such in the magmas, because certain chemical combinations may take place immediately after vapors and gases escape into the air before they can be collected and studied.

**Lavas.** *Lava streams.* The molten materials which issue from volcanoes and fissures in the earth, as well as the rocks which result from their cooling, are called *lavas*. When they are in a molten condition, such materials are known as *magmas* (Fig. 164). The temperature of magmas is very high, commonly ranging from 1500° F. to 2500° F. In a general way, increase in the percentage of oxide of silicon (same in composition as quartz) in the various minerals of the magma decreases the temperature necessary to keep the material molten. Increase in gases and vapors (particularly water vapor) in magma also decreases the temperature necessary to keep it molten.

During many volcanic eruptions, magma rises in the crater until it pours over the edge, and flows down the side of the mountain in one or more streams, much as would streams of molten iron (Fig. 165). Lava is white-hot when at a high temperature, and in a highly fluid condition, but it soon changes to a dull-red glow after it leaves the vent. As the magma flows down the mountain and gradually cools, it becomes a thicker liquid (that is, more viscous), some minerals begin to crystallize

in it, and finally the whole mass becomes solid lava. A thick lava-flow requires months or even years to become thoroughly cooled. Lava streams are very commonly from one-fourth to one-half of a mile wide, and from 25 to 100 feet or more deep.

Streams of lava do not always pour out of summit craters of volcanoes. They may break out of the sides of the cones, as has invariably happened in the case of the great active volcano of Mauna Loa, Hawaii, during the last 125 years. In such cases the pressure necessary to lift the columns of molten lava to the summits of the mountains is so great

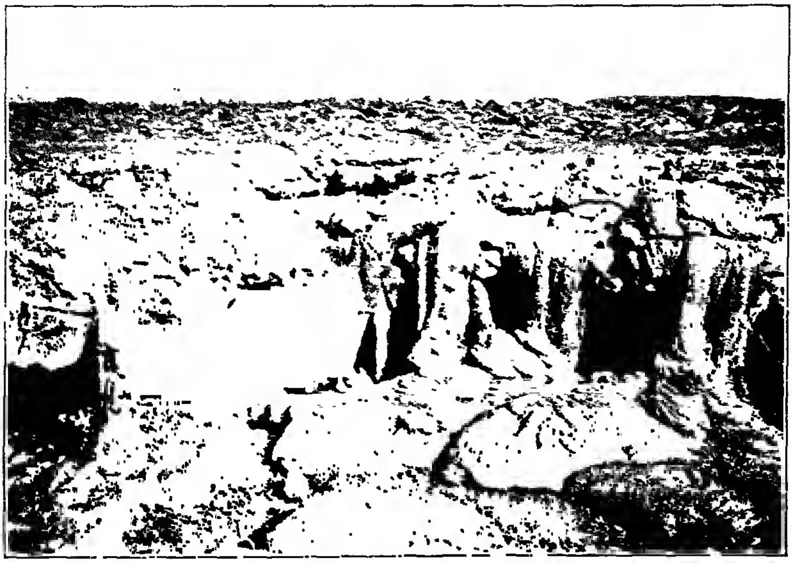


FIG. 166. A lava-flow over the edge of an old lava tunnel. Kilauea, Hawaii.

that relief of the pressure takes place by development of one or more fissures on the flanks of the cones out of which the molten lavas pour.

During the process of flowage and cooling of a lava stream, a time comes when there is a strong tendency for a hard, relatively cold crust to form over the still molten material underneath. It is often possible to walk in comparative safety over such crusts. Molten material of a lava stream may, under favorable conditions, drain away under its hardened crust, leaving a long, narrow, more or less winding cave, or so-called *lava tunnel.* Such tunnels, which usually range in length from a few hundred feet to several miles, and in diameter from 20 to 50 feet, are often remarkably smooth and regular inside (Fig. 168). Under

other conditions, the irregular movement of the lava stream may cause its crust to be broken to pieces, and no tunnel results.

A stream of lava in a very hot, highly fluid condition usually flows down a fairly steep mountainside at the rate of from a few miles per hour to perhaps 10 or 20 miles per hour. As it cools, however, the magma becomes thicker and more viscous, and its rate of motion slowly diminishes until it finally stops. It is not uncommon for streams of lava in Hawaii to continue a slow movement for weeks, or even months.

The distance which a lava stream flows is determined by several factors such as temperature, degree of fluidity, kind of molten rock and steepness of slope. Lavas like those of Hawaii and Iceland are of

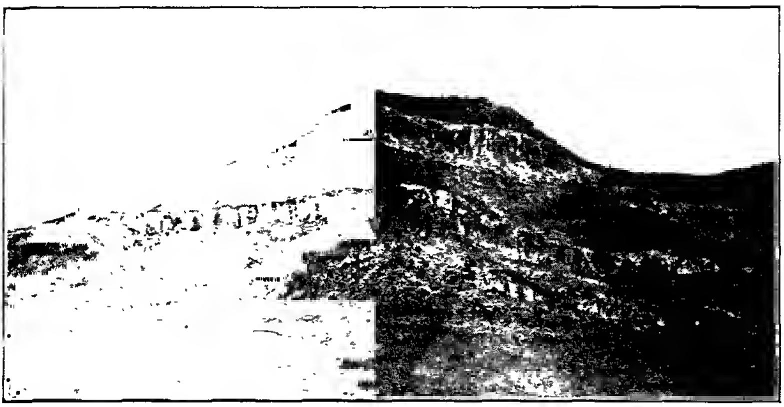


Fig. 167. Lava sheets, representing successive lava-flows, exposed by erosion. Near Pahroc Springs, Nevada. (Photo by C. D. Walcott for U. S. Geological Survey.)

such a nature that they remain fluid at exceptionally high temperatures for so long that they have commonly flowed for 10 to 25 miles, and, in some cases, even 30 to 50 miles. Extreme cases to the contrary are where lavas are so viscous that they pile up close around the vents as shown by certain recently extinct volcanoes of France and Germany.

*Kinds of lavas.* When lavas solidify from a molten condition they have either a glassy or a stony appearance. Volcanic glass (Fig. 35), called *obsidian*, is much less common than stony lava. It results from very rapid cooling, especially of the more viscous magmas rich in oxide of silicon. Such a condition is unfavorable for the molecules to build themselves together in the form of crystals, which would give the rock a grained, or stony, appearance. Volcanic glass is, among many other

places, finely exhibited in Obsidian Cliff in Yellowstone Park, and near Mono Lake, California.

Stony lavas constitute the great bulk of rocks which form from magmas at, and very near, the earth's surface. For their development, the magma must be sufficiently fluid, and time enough must be given during the cooling, for crystals (usually small ones) to form. The lava may be wholly crystalline, or crystals may be distributed through a glassy groundmass. The mineral composition of some of the most common kinds of lavas—*basalt, andesite, trachyte,* and *rhyolite*—and their relations to other common types of igneous rocks have already been considered.

FIG. 168. Detail view in a lava tunnel 40 feet high. Gular, Washington. (Courtesy of the U. S. Forest Service.)

If, during the cooling of a surface magma, some minerals form well-defined crystals scattered through the mass, and then the remaining material solidifies with little or no crystallization, a so-called *porphyritic lava* (Fig. 34) results, that is, one with relatively large mineral grains embedded in a much finer grained, or glassy, groundmass.

Escape of gases and steam through the upper portion of a lava-flow, where the pressure is slight, may fill it with bubbles so that on cooling it becomes *cellular lava* (Fig. 172). If the bubbles are large, giving the rock a spongy appearance, it is called *scoria.* If the bubbles are small, very numerous, and exceedingly thin-walled so that the rock is exceptionally light, sufficiently so at times to float on water, the lava becomes *pumice* which is really igneous-rock froth.

Two Hawaiian terms are commonly used to designate the general character of the surfaces of lava-flows. One of these is *pahoehoe* which is applied to generally smooth, though often curved and billowy, surfaces of lava (Fig. 170). The other is *aa* which refers to rough, jagged, badly broken up surfaces, caused either by more or less violent escape

FIG. 169. Wavy, porous lava still hot and steaming. Kilauea, Hawaii.

FIG. 170. Detail view of so-called "pahoehoe" lava at the end of a three-mile flow. Kilauea, Hawaii.

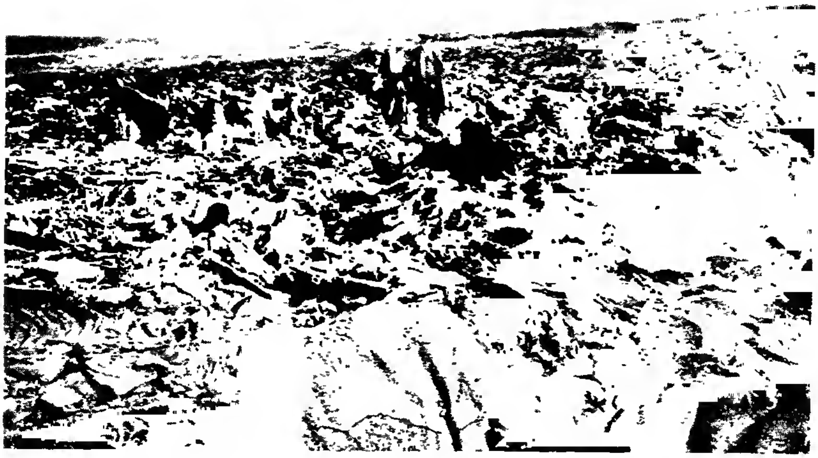


FIG. 171. Part of a field of rough, broken lava (so-called "aa"). Kilauea, Hawaii.

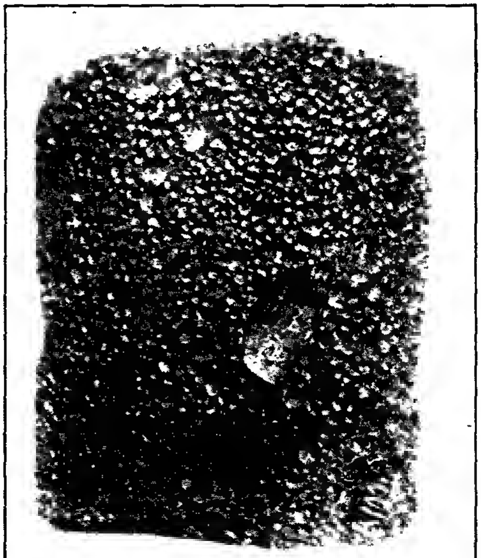


FIG. 172. A specimen of cellular lava.

of gases or steam, or by the breaking up of a hardened crust by movements of viscous lava underneath it (Fig. 171).

**Fragmental Products.** These are the materials (usually heated) which are thrown into the air by the explosive action of a volcano, and fall to the ground as solid fragments. They vary in size from the tiniest dust particles, to masses of tons weight.

*Blocks and bombs* are pieces of rock, from about an inch to several feet in diameter, which are hurled out of volcanoes. They may be more or less angular blocks torn loose

in solid condition, or they may result from violent disruption of molten material whereby masses of the magma, in whirling through the air, take on somewhat rounded forms, and solidify as such. Bombs of the latter sort are often cellular (Fig. 173), or even pumiceous due to escape of gases.

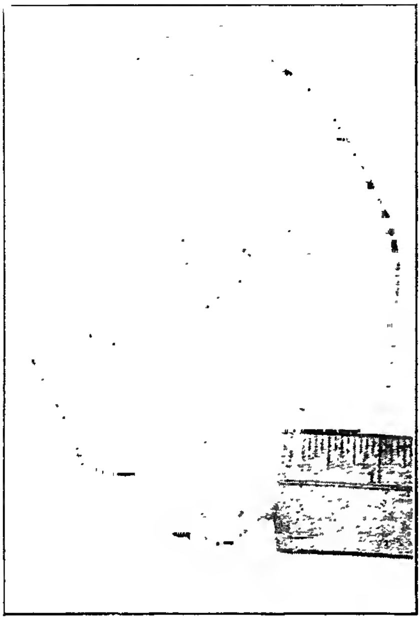


FIG. 173. A volcanic bomb from southern Idaho.

*Volcanic cinders* are fragmental materials ranging in size from about an inch down to dust particles. Larger cinders are called *lapilli*, and smaller ones are called *volcanic ashes*. Both types may or may not be porous. The terms "cinders" and "ashes" are good only in the sense that they suggest a resemblance to familiar products of burning, but they are not results of combustion. More or less well-defined beds or layers of the larger fragments (blocks, bombs, and cinders) produced by successive eruptions, and cemented with ash or other substances, form *volcanic breccia*.

*Volcanic dust* is the most finely divided material ejected from volcanoes. Successive eruptions often cause volcanic dust and ashes to accumulate in more or less well-defined layers or beds which become compacted into so-called *tuff*.

## CHARACTER OF ERUPTIONS

**Effusive Type.** Volcanoes characterized by effusive eruptions are relatively quiet in action, and comparatively free from severe explosions. The two great active volcanoes of Hawaii—Mauna Loa and Kilauea—are excellent examples of the effusive type. They are briefly described beyond in this chapter.

Volcanic cones built up wholly, or largely, by many effusive eruptions are generally characterized by having large craters (or calderas), low angles of slope (usually less than 10°), and great basal diameters. The two last named features are due to the fact that the lava streams tend to flow far out from the vents.

**Explosive Type.** Volcanoes characterized by explosive eruptions are violent in action. In extreme cases the top of a cone, or even almost the entire cone, may be blown to pieces and widely scattered. An example of extreme violence was that of Katmai in 1912, described beyond. Typical explosive volcanoes seldom yield lava streams, but they commonly send great clouds of volcanic dust and ashes, mingled with steam, high into the air. Large blocks of rock are also often hurled out.

Volcanic cones built up largely by explosive eruptions generally have well-defined craters; their sides are steep (up to 30 or 40 degrees); and

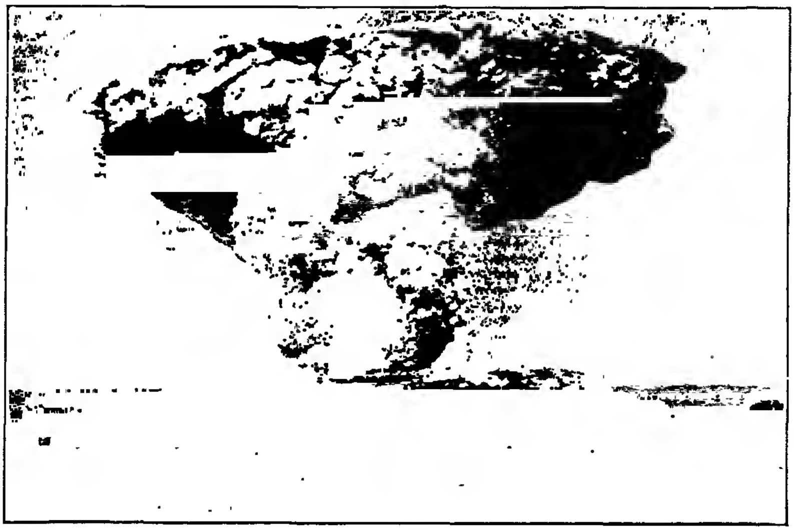


FIG. 174. The grand eruption of Lassen Peak, California, May 22, 1915. The volcanic cloud is fully 8 miles high. Photo taken at Anderson, 50 miles away. (Photo by courtesy of Myers and Loomis.)

the diameters of their bases are relatively small. The two features last mentioned are due to the fact that most of the materials, in solid form, particularly the coarser fragments, accumulate relatively close around the vents, and produce slopes much steeper than lava-flows. *Cinder cones*, built up by explosive eruptions of volcanic cinders, belong in this category (Fig. 175).

**Intermediate Type.** Most of the volcanoes of the world, especially the larger ones, are neither typically effusive nor explosive in action, but rather intermediate between the two. They are characterized by more or less alternation of eruptions of lava streams and fragmental

materials. Mt. Shasta, California, and Mt. Rainier, Washington, are the two greatest volcanic cones of the intermediate type in the United States. The active Mt. Vesuvius is another good example. Such cones are usually rather steep-sided, that is, their slopes are often 20° to 30°.

**Fissure Eruptions.** It has already been suggested that not all volcanic materials are erupted from cones. Eruptions may take place through fissures, both small and great, in no way connected with volcanoes in the ordinary sense of that term. The materials thus erupted are always molten rather than fragmental. Some of the best exhibitions of fissure eruptions during the last century and a half have been those of Iceland. Thus in 1783 molten lava poured forth from many places out of a fissure 20 miles long. One of the streams of lava was nearly 50 miles long, and another nearly 30 miles long. Each was several miles wide. As late as 1923, molten lava welled out of a number of very small craters arranged along a fissure and spread out.

Fissure eruptions have, in past ages, produced vast fields of lava of great depths, as for example the Columbia Plateau covering 200,000 square miles in the northwestern United States.

**Domal Eruptions.** When a magma is too viscous to flow, it may be forced out of a vent in the form of a steep-sided, more or less dome-shaped mass, called a *volcanic dome,* as in the case of Lassen Peak, California.

## Age and Destruction of Volcanoes

**New Volcanoes.** A considerable number of relatively small volcanic cones are known to have been built up during the Christian era. Some of these have developed on land, and some in the sea, forming islands. A few examples will be given.

Monte Nuova, a cone 440 feet high near Pozzuoli, Italy, was built up in 1538. A vent was formed by bending up and breaking the ground. Glowing lava was visible, and eruptions of fragmental materials continued for about a week, building up the cone. There have been no eruptions since. The cone stands among others which are not much older.

A remarkable case is that of Jorullo, Mexico, where a volcano burst forth in cultivated fields one day in 1759. Eruptions continued for several years. Large quantities of both molten and fragmental materials were ejected, building up a cone to a height of several thousand feet. A little later (in 1770), activity started at Izalco in San Salvador.

FIG. 175. An aerial view of recent cinder cones and a lava-flow. The lava-flow, five miles long, emerges from the base of a cone and spreads out. About forty miles southeast of Grand Canyon, Arizona. (Fairchild Aerial Surveys.)

Eruptions, often violent, have been almost continuous since that tin. and a cone over a mile high has been formed.

Cinder Cone (640 feet high), and its associated lava field of several square miles, came into existence in northeastern California as a result of eruptions which began not longer ago than the early part of the 6th century. The second and last lava-flow, which poured out during the middle of the 19th century, is probably the youngest in the United States.

In 1831 vigorous volcanic activity on the floor of the Mediterranean

FIG. 176. A considerably eroded, recently extinct volcano. Mt. Shasta, California. (Photo by courtesy of the Southern Pacific Lines.)

Sea caused an island of fragmental material 200 feet high to be formed. In a relatively short time it was cut away by wave erosion.

In the Santorin Islands of the Greek Archipelago, several small islands have been formed by volcanic activity during the last 2000 years.

A number of spectacular eruptions in the Aleutian Islands of Alaska, particularly in 1796, 1883, and 1906, have resulted in the formation of islands in the sea.

Various cinder cones in Arizona (Fig. 175) and eastern California are so fresh and unaffected by erosion that they certainly cannot be more than a few hundred, or at most a few thousand, years old.

**Duration of Volcanic Activity.** Volcanoes have sometimes been classified as active, extinct, and dormant. Such a classification is, however, not very satisfactory because, as has so often happened, a volcano which has been inactive for many years may again break forth. Mt. Vesuvius in Italy, and Lassen Peak in California, are among many examples.

The length of time during which individual volcanoes remain more or less active is exceedingly variable, ranging from a few days (or less) to hundreds of thousands, or even millions, of years. Most of the great volcanoes of the present time began their activity in the latter part of the present (Cenozoic) era. They are, therefore, several million

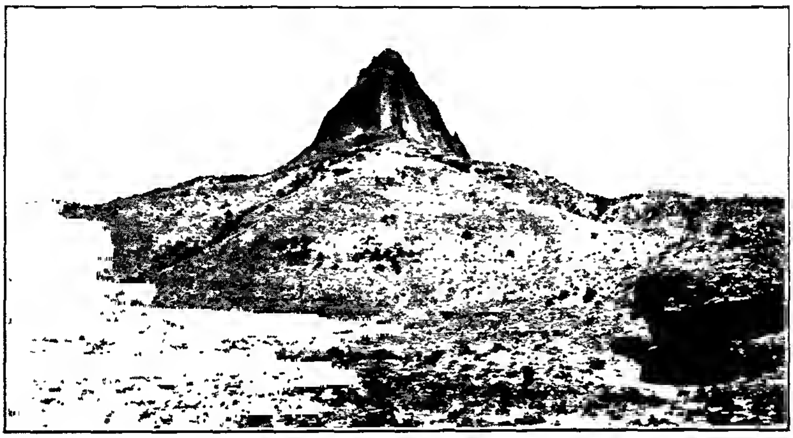


FIG. 177. A volcanic neck. Mt. Taylor region, New Mexico. (After Dutton, U. S. Geological Survey.)

years old. Some of them, like Kilauea, are now constantly active; some, like Mauna Loa and Mt. Etna, are very active at intervals of a few years; others, like Mt. Shasta and Mt. Raimer, are either dormant or practically extinct; while still others, like Mt. Crandall in Yellowstone Park, ceased action so many hundreds of thousands of years ago that the great cones, many miles in diameter, have been very largely removed by erosion.

**Destruction of Volcanoes.** In some cases volcanic cones are partly, or almost wholly, destroyed through their own explosive activity. Thus an explosion of terrific violence in Katmai Volcano, Alaska, in 1912 blew away several cubic miles of the top of the mountain (Fig. 179), and the explosion of Krakatoa in the East Indies in 1883 almost com-

pletely obliterated what was a fair-sized cone. A cone may be partially destroyed by engulfment or subsidence of its upper portion due to weakening of the support underneath. The great crater (or caldera) of Mt. Mazama, containing Crater Lake, in southern Oregon was probably thus formed (Fig. 211).

The destructive work of weathering and erosion is, however, the greatest cause of obliteration of volcanic cones. Every volcanic cone, even when in course of construction, is subjected to the attacks of weathering and erosion. The upper part of the cone of Mt. Vesuvius

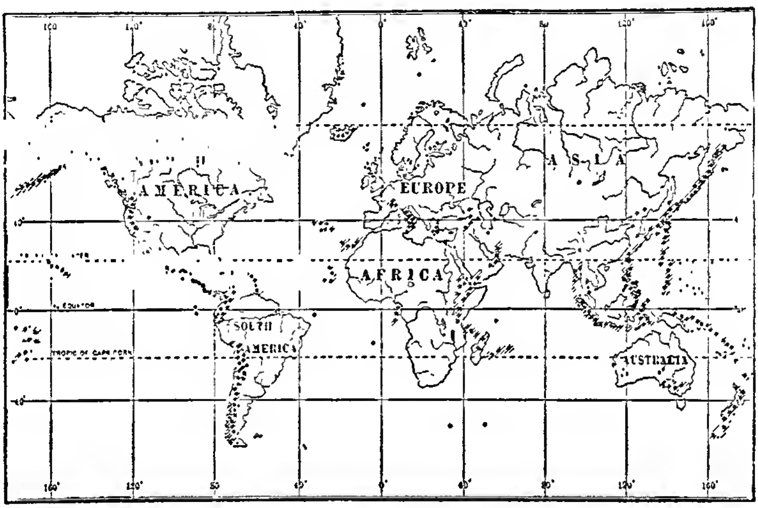



FIG. 178. Map showing the distribution of active and recently extinct volcanoes. (From Tarr's "New Physical Geography," by permission of the Macmillan Company.)

was, for example, distinctly trenched by erosion soon after the great eruption of fragmental materials over its sides in 1906. When, barring very violent eruptions, the amount of material ejected by a volcano is greater than can be removed by erosion, the cone continues to build up. The activity diminishes and finally ceases, after which the cone becomes more and more deeply dissected (Fig. 176), its crater becomes obscured, and its height gradually becomes lower. During a late stage of its erosion, nothing but the core or plug of the volcano may rise above the general level of the country (Fig. 177), and finally it may completely vanish as a topographic feature.

## Submarine Volcanoes

It has already been suggested that volcanic activity may take place on the floor of the sea. A remarkable example is Mauna Loa, Hawaii, which began action at the bottom of the mid-Pacific Ocean where the water was fully three miles deep. It has been built up into a gigantic, gently sloping cone nearly 14,000 feet above sea level. All of the eight Hawaiian Islands mark the highest portions of a great submarine volcanic ridge or range several hundred miles long.

A remarkable case of a great mountain range being built up out of the sea is the chain of Aleutian Islands, Alaska, more than a thousand miles long. It contains various active volcanoes—three new ones (the Bogoslov volcanoes) having been built up as islands in the years 1796, 1883, and 1906.

Among many other examples of volcanoes of submarine origin, mention may be made of the Azores, Cape Verde Islands, Canary Islands, and various islands of the South Pacific Ocean. Mention has already been made of the cone (Graham's Island) which was built up by eruptions in the midst of the Mediterranean Sea in 1831.

## Distribution of Active and Recently Active Volcanoes

Hundreds of volcanoes are definitely known to be active, and several thousand others are either dormant, or have become extinct in very recent geologic time, that is, during the latter portion of the present era. Most of these volcanoes show a strong tendency toward arrangement into two grand zones or belts (Fig. 178). One of these belts nearly encircles the Pacific Ocean, extending through western South America, Central America, western North America, the Aleutian Islands, Kamchatka, Japan, the Phillippine Islands, the East Indies, the New Hebrides, and New Zealand. There are of course various local portions of this belt without volcanoes. The other great belt is less well-defined and more interrupted. Beginning, let us say, in Central America, it extends through the eastern part of the West Indies, the Azores, the Canary Islands, the Mediterranean region, Asia Minor, southern Arabia and eastern Africa, eastern India, the East Indies, and the Hawaiian Islands. A considerable number of volcanoes lie outside of the two grand belts.

Various ideas have been expressed in the attempt to explain the distribution of most of the active and recently active volcanoes in the two great belts. Without entering into this discussion, suffice it to say that

these volcanoes occur in zones where earth-crust disturbances have been recently, and are now, unusually pronounced. They are, in other words, in zones of exceptionally active mountain-building movements. These

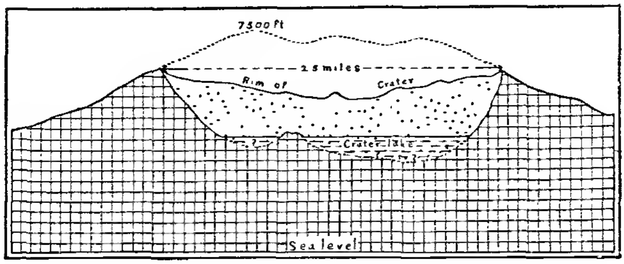



FIG. 179. Diagrammatic section showing the condition of Katmai Volcano, Alaska, before and after the great eruption of 1912. (Drawn by the author, data from National Geographic Society.)

zones are, in a general way, also the belts of greatest earthquake activity, and, as already stated, both earthquakes and volcanoes are but surface and near-surface manifestations of deeper-seated and more profound earth-crust activity.

## Some Great Volcanic Eruptions

**Mauna Loa and Kilauea.** Two of the most interesting, readily accessible, great volcanoes are Mauna Loa and Kilauea on the island of Hawaii in the midst of the northern Pacific Ocean. They are fine illustrations of the effusive, or relatively quiet, type of volcano. Mauna Loa is an exceedingly large volcanic pile with very gently sloping sides rising to nearly 14,000 feet above the sea, and Kilauea lies on its flank at an altitude of about 4000 feet. Each has a vast, oval-shaped crater nearly three miles long bounded by nearly vertical walls of lava many hundreds of feet high. Each crater pit has a nearly level floor consisting of hard, fresh, black lava which is really only a crust covering a mighty column of molten lava, several miles in diameter, extending far down into the mountain. Prior to an eruption, the lava column in Mauna Loa rises hundreds of feet in the crater, but, during the last century at least, it has not overflowed the rim. Instead, at intervals of about 5 to 12 years, the lava breaks out of the mountainside in the form of a molten stream, somewhere within a few thousand feet of the summit of the cone. The resulting relief of pressure causes the column of lava in the crater pit to subside slowly. Many such streams of molten lava, from one-fourth of a mile to a mile wide, have flowed down the sides of the mountain 10 to 45 miles, sometimes even into the sea. The great lava stream of 1919 entered the sea, and poured into it for weeks, after flowing about 15 miles from the source on the flank of the mountain.

Important flows also occurred during 1926 and 1935. Between eruptions, Mauna Loa shows no signs of real activity.

Kilauea acts in general much like Mauna Loa. Lava streams have poured out of its flanks also at various times, in each case preceded by a rise of the lava column in the vast crater pit. Within the mighty crater bowl of Kilauea, there is, however, an inner pit or crater, about three-fifths of a mile in diameter, marking a place where the crust of the great column of molten lava in the throat of Kilauea is usually broken through, revealing the magma (Fig. 164). Within this nearly circular inner pit, with its vertical walls, the molten lava rises and sinks hundreds of feet within periods of a few years. Sometimes the magma overflows the pit and streams out upon the wide floor of Kilauea (Fig. 166).

**Katmai Volcano.** Within two days in June, 1912, Katmai Volcano in southern Alaska was subjected to several terrific explosions which were probably of even greater violence than those of Krakatoa. The cone, which rose over a mile above the surrounding country, had its whole upper portion, involving about 5 cubic miles of rock, blow away, leaving a vast crater (or caldera) two and one-half miles in diameter and several thousand feet deep (Fig. 179). This crater is now one of the world's largest. The first and greatest of the three explosions was heard in Juneau, Alaska, 750 miles away. The product of the explosions was mainly dust which fell to a depth of one foot in a village 100 miles away, and in perceptible amounts 900 miles away in southeastern Alaska. Dust and larger fragments fell to depths of from 2 to 10 feet on the flanks of the beheaded mountain. Glaciers on the mountain were truncated, leaving walls of ice over two miles long capping part of the crater rim. Severe earthquakes accompanied the explosions.

**Mt. Vesuvius.** Excellent examples of volcanoes of the intermediate type are Vesuvius and Etna. For centuries prior to the Christian era, Mt. Vesuvius seems to have been inactive. From 63 to 79 A.D., numerous earthquakes shook the mountain and vicinity. Then, in the year 79, there occurred the most violent eruption of the mountain in historic times. No molten lava appeared, but the explosion blew away much of the upper part of the cone, greatly altering its outline, and leaving a conspicuous crescent-shaped ridge around part of the stump of the mountain. "Ashes fell upon the surrounding country, a huge column of steam and ash darkened the sky, and great torrents of water fell upon the flanks of the mountain. Pompeii was buried beneath a cover of ash and dust which penetrated every crevice, and so sealed the objects in a compact cover. In the excavations which have been made during the last century, objects of even a perishable nature have been recovered. . . . It is a wonderful experience to walk through the deserted streets of this ancient city of 20,000 inhabitants, to realize under what terrible conditions the people were driven out or overwhelmed in their efforts to escape" (Tarr and Martin).

Among the many eruptions of Mt. Vesuvius since 79 A.D., mention may be made of those of 1872 and 1906 when great clouds of ashes and

dust were thrown miles into the air and streams of lava flowed down the mountainside.

**Lassen Peak, California.** In conclusion, brief mention may be made of Lassen Peak in northern California which is of special interest not because of the magnitude of eruptions, but because it is the most recently active volcano in the United States proper. The steep-sided cone of Lassen rises about a mile above the surrounding country. Prior to May 30, 1914, the mountain had been inactive for hundreds, or even thousands of years, as judged by the state of weathering of its crater. On the date mentioned, the old volcano suddenly burst into explosive activity, and hundreds of eruptions occurred within the next few years. Little or no lava appeared, but great clouds of steam and dust were shot into the air, often to heights of several miles (Fig. 174), and scattered ten to thirty miles around the mountain. During a grand eruption of 1915, a tremendous volume of condensing steam mingled with volcanic dust started down the eastern face of the cone, causing the snow to melt. The resulting flood of hot mud and loose rock fragments, together with the very hot volcanic cloud, rushed with terrific speed to the base of the cone, and into a beautiful mountain valley, leaving an appalling scene of desolation for ten miles. Forests were swept away for miles, and fires were set. Real eruptions ceased in 1917, but some steam still escapes within the crater.

# CHAPTER XII

## SUBSURFACE WATER

### Sources, Amount, and Disposal of Subsurface Water

The source of all but a very small quantity (probably not over one per cent) of the subsurface water in the zone of fracture, or outer, crustal portion of the earth, is atmospheric precipitation, that is, rainfall and snowfall. It has been estimated that about 1500 cubic miles of water (including its frozen state—snow) falls upon the surface of the United States yearly. One-half, or somewhat more, of this evaporates; about one-fourth of it flows off in surface streams; and the remaining one-fourth, or somewhat less, works its way into the crust of the earth either by soaking into loose materials, or by entering cracks, fissures, and other openings in the bedrock.

Some conception of the quantity of ground water may be gained from the statement, based upon a careful estimate, that all of the water in the soils and rocks of the first 100 feet below the surface of the United States would be sufficient to form a surface layer 17 feet thick. In the sections of the country with humid climate, the amount of water in the first 100 feet would of course be greater than the average. It should not be assumed, however, that anything like such a proportionate amount of water in rocks continues to depths of miles, or even of thousands of feet. The absolute limit of depth beyond which any very appreciable amount of ground water, in the ordinary sense of that term, can exist is only about 8 to 12 miles, depending upon the hardness of the rocks. This is because the tremendous pressure of the overlying rocks makes it impossible for very appreciable openings to exist beyond such depths. Very little surface water ever reaches such extreme depths. Most of the underground water by far occurs within a few thousand feet of the surface. This conclusion is borne out by the fact that, in deep mines in various parts of the world, little or no water is usually encountered lower down than a few thousand feet. Large fissures containing water are, however, sometimes found in deep mines. Some moisture no doubt is held in the pores of the rocks beyond depths of a mile or more.

What becomes of the water which descends into the earth's crust? A large amount returns to the surface through springs and seepages; a large amount moves to the surface by capillarity in loose rock materials, and then evaporates; plants absorb much water which is drawn up into the leaves to be evaporated; a considerable amount is removed through

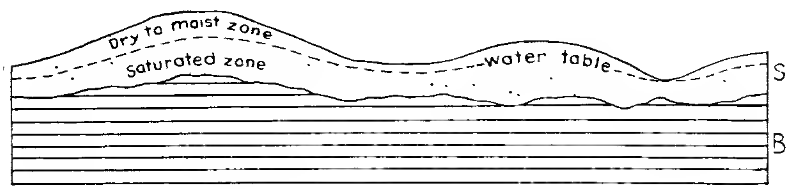



FIG. 180. Structure section showing soil (S) with water table resting upon bedrock (B).

wells; some travels underground to emerge as springs in the sea relatively near shore, as is known to be the case in the Gulf of Mexico, and in the Mediterranean Sea; some enters into chemical combination with various minerals and rocks to be held there, often for ages of geologic time; and some makes its way so far down in crevices and pores of the rocks that it remains for a very long time.

## Modes of Occurrence of Subsurface Water

**Water in Loose Rocks and Soils near the Surface.** There are three general modes of occurrence of subsurface water: (1) In loose materials relatively near the surface; (2) in porous consolidated rock layers or formations, usually well below the surface; and (3) in cracks, fissures, and other openings in hard rocks. Loose rock formations and soils are, in most humid regions, saturated with water at greater or less depths (usually less than 75 feet) below the surface. This statement is borne out by the fact that water may be obtained almost universally from wells in such regions within 25 to 75 feet of the surface. More or less moisture of course occurs in the materials above the zone of saturation. In arid and semi-arid regions there is often no zone of saturation in the loose, incoherent materials just below the surface, or in case it is present, it is usually farther down than in humid regions.

The porosity of many loose soils and rocks is surprisingly high. Thus 25 to 40 per cent of the volume of common sand is pore space, while in loam it is usually 40 to 50 per cent. It is clear, therefore, that

one-fourth to one-half of the volume of such material, when saturated, is water.

**Water in Porous Rock-layers.** Very considerable amounts of water occur in more or less definite layers or formations which often extend at various angles for hundreds, or even some thousands, of feet into the earth. Such water-bearing layers or formations are known as *aquifers*. An aquifer is usually bounded above and below by material rather impervious to water (Fig. 181). An excellent example of an aquifer on a large scale is the Dakota sandstone formation of South Dakota and Nebraska. Almost anywhere across Nebraska, a well drilled through a thick formation of clay, and into the porous Dakota sandstone, strikes water. In such an aquifer, water travels long distances. Thus water obtained from a well in the Dakota sandstone formation in eastern Nebraska has traveled actually hundreds of miles under the state from the eastern front of the Rocky Mountains where surface water entered the upturned and exposed edge of the porous formation.

Among the consolidated strata, sandstones and certain limestones are usually the most porous, their volumes of pore space often being 20 to 30 per cent.

**Water in Cracks and Other Openings in Hard Rocks.** The least amount of subsurface water occurs in the hard, bedrock formations. With the exception of the small quantity rather firmly fixed in the tiny pores of the rocks, most of such water occurs in joint cracks, fault frac-

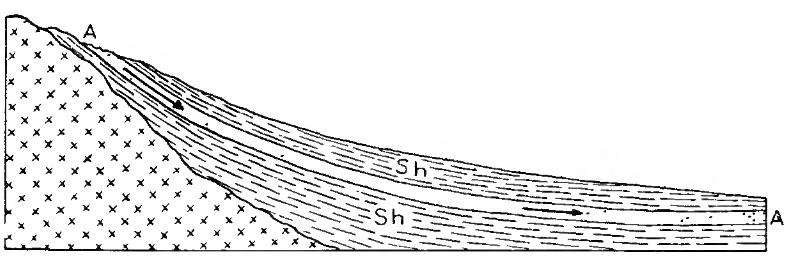



FIG. 181. Structure section showing an aquifer (A-A) lying between nearly impervious beds of shale (SH). Arrows indicate direction of movement of water in the aquifer which may extend for many miles.

tures, or more or less well-defined channels. Many formations, such as granite and other types of crystalline rocks, are neither in definite layers, nor are they porous enough to permit water really to flow through their masses. The porosity of hard, deep-seated igneous and metamorphic rocks is generally less than one per cent.

We have already learned that joint cracks are very common, and usually closely spaced, in all kinds of hard rocks in the outer (zone of fracture) portion of the earth's crust. Such cracks are usually more or less irregular in both direction and spacing. Fault fractures, which are not so abundant, are often rather regular and straight for considerable distances. As would be expected, the ease with which water may travel along such cracks and fractures varies greatly. Many times the passageways are sufficiently long and open to permit water to follow them readily for hundreds, or even thousands, of feet.

In limestone, even where it is exceptionally dense, and to a less extent in other rocks, underground water often enlarges passageways into more or less distinct channels along which actual underground streams may flow. Such streams may reach the surface in the form of springs. Echo River, which flows through the bottom of Mammoth Cave, Kentucky, is a fine large-scale example.

In a great lava region, such as the island of Hawaii, subsurface water often flows through lava tunnels, the origin of which we have already explained.

**The Water Table.** The surface below which the soils and rocks are saturated with water is called the *water table* (Fig. 180). The term does not apply to a saturated layer or formation (*aquifer*) capped by an impervious layer or formation. The water table most typically lies in soil which rests upon bedrock in a humid region. In such a place surface water works downward, filling all cracks and crevices in the bedrock, and saturating the lower portion of the soil, while the upper portion of the soil is only moist. The top of the saturated zone is the water table. It has already been suggested that there is no universal zone of saturation, particularly in arid regions.

The water table is very irregular, but it is generally farther under the surfaces of hills than of valleys. This is because the water at the higher levels tends to migrate, under the action of gravity, to the lower levels. After prolonged rain, the water table may coincide almost, or quite, with the earth's surface over a considerable area, as was the case at the time of the Dayton, Ohio, flood of 1913 when the ground was nearly everywhere thoroughly soaked, causing a maximum run-off. In the soil-covered, humid portions of the United States, the water table ranges very commonly in depth from the surface to 40 or 50 feet. Springs, swamps, ponds, and lakes not infrequently mark places where the surface of the ground either intercepts, coincides with, or passes below the water table (Fig. 180). The water table lowers steadily

during long periods of dry weather, and this explains why so many wells, springs, and swamps, which are dependent upon the upper portion of the saturated zone, go dry.

## Springs

**Ordinary Springs.** The term *spring* is applied to subsurface water which emerges from the ground. Springs may be divided, according to their modes of origin, into gravity and artesian springs, and, according

Fig. 182. Springs issuing from a bed of gravel between layers of lava. Thousand Springs, Idaho. (Courtesy of the U. S. Reclamation Service.)

to the nature of the passages traversed by the water, into seepage, tubular, and fissure springs. Some of the most common conditions under which springs occur are illustrated by the accompanying figures.

**Hot Springs.** *Hot springs* may be regarded as those whose temperature ranges from that of the human body to the boiling point of water. The two most common causes of the heating of the waters of hot springs are the following: (1) The water may pass through masses of volcanic rocks of recent geologic age which have not yet cooled to the normal temperature of the earth's crust. Yellowstone National Park contains thousands of such hot springs (many of them boiling) where, during the present (Cenozoic) era, successive outpourings of lava covered a wide area many hundreds of feet deep. Fine examples also occur in the Lassen Peak region of northern California, and in many other parts

of the world. (2) Water may, where the rock structure is favorable, pass far enough below the surface to have its temperature notably raised by the general heat of the earth's interior, and then rise to the surface under (hydrostatic) pressure. Deep well records show that the temperature of the earth increases downward at the rate of about 1° F. in 50 to 75 feet. Water emerging from a depth of a few thousand feet

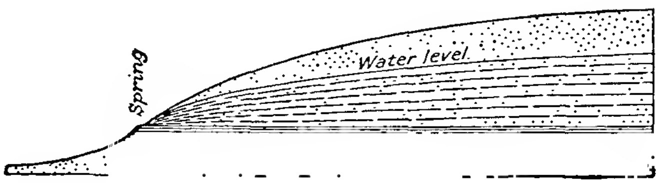



FIG. 183. Diagrammatic section illustrating a water-table spring. (After U. S. Geological Survey.)

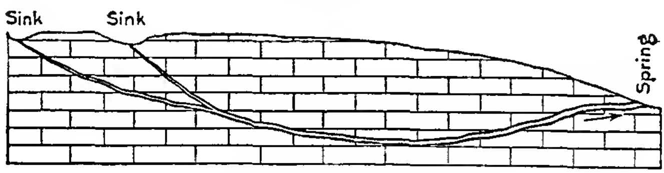



FIG. 184. Diagrammatic section illustrating a tubular spring in limestone. (After U. S. Geological Survey.)

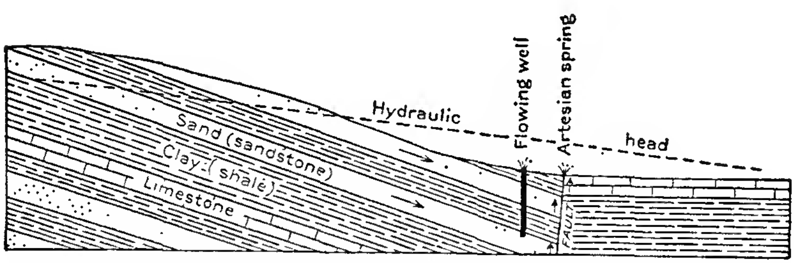



FIG. 185. Diagrammatic section illustrating a fissure (or artesian) spring. (After U. S. Geological Survey.)

would, therefore, be notably warm. Such springs are, however, usually not very hot, and rarely, if ever actually boiling. They emerge usually from prominent fault fractures which extend to great depths, generally where the rocks are also much folded. There are many examples in the southern half of the Appalachian Mountains, as at Hot Springs, Virginia. Among many other examples are Hot Springs, Arkansas; near Ogden, Utah; and in parts of southern California.

Other sources of heat of underground water may be chemical action; friction due to rubbing of rock masses against each other, as during faulting; and possibly radio-activity, but these are probably much less important than the two sources above explained.

*Geysers* are periodically eruptive hot springs found only in a few of the recent volcanic regions of the world, such as Yellowstone Park, Iceland, and New Zealand. They are exhibited most wonderfully in Yellowstone Park where many of them erupt columns of hot water to heights of 25 to 250 feet at intervals varying from an hour or less to

FIG. 186. A group of hot springs and geysers. Yellowstone National Park. (Photo by Hillers, U. S. Geological Survey.)

many days (Fig. 170). Old Faithful Geyser erupts once about every 70 minutes, each time sending over a million gallons of hot water, in the form of a column several feet in diameter, to a maximum height of about 200 feet.

The general explanation of geyser action may be stated briefly as follows: The very irregular geyser tube extends downward nearly vertically into a mass of hot lava. The tube is filled with water from openings in the immediately surrounding rocks. The boiling point of the water toward the bottom of the tube is considerably greater than it is at the surface because of the pressure of the column of water. Finally, however, the hot lava causes the water to boil far down in the tube, in spite of the pressure. The first steam to form causes the whole column of water to lift slightly, thus relieving the pressure on the superheated water far down, and resulting in a quick development of much

steam which violently forces most of the water out of the geyser tube. Then the process is repeated.

**Mineral Springs.** Water begins to take mineral matter into solution as soon as it enters the earth. In many cases, particularly where the material is relatively soluble, or where the water travels far down, much material may be taken into solution, causing the water to become more or less highly mineralized. Such water, emerging at the earth's surface, forms a *mineral spring* which may be cold or hot. Mineral springs, and also wells, often yield so-called hard water which contains much calcite, dolomite, gypsum, or certain other mineral salts in solu-

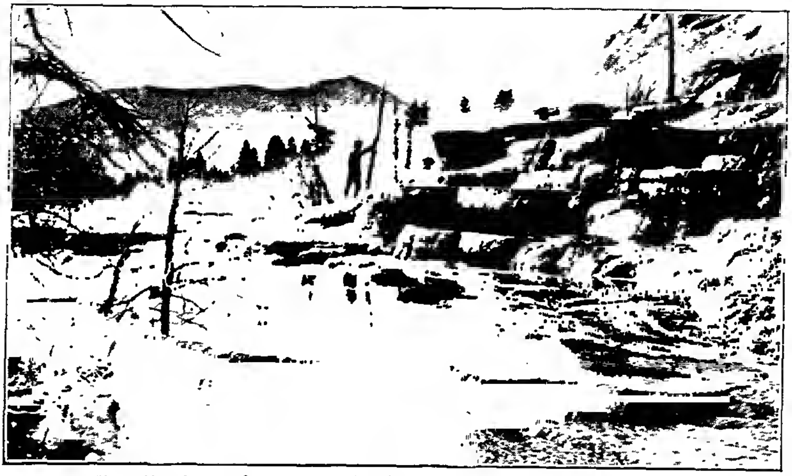


FIG. 187. Detail view of a part of Mammoth Hot Springs, Yellowstone National Park. (Photo by Jackson, U. S. Geological Survey.)

tion. Wells and springs in limestone regions characteristically yield hard water. Soft water usually emerges from openings in igneous rocks, such as granite and lava, and from other rocks which contain very little limy matter. Mineral waters may contain sulphuretted hydrogen, carbonic acid gas, and other gases. A carbonated spring is highly charged with carbonic acid gas which escapes from the emerging water on account of the relief of pressure. Mineral springs may be either hot or cold. Mineral waters are often more or less medicinal in their effects.

## Wells

**Kinds and Depths of Wells.** Water wells are sunk in various ways, the most common of which will be mentioned. Most wells by

far are simply *dug* down in loose materials to a little below the water table. The depth seldom exceeds 50 feet in humid regions. Wells are often *bored* in loose materials with large augers, rotated by a power-developing machine, to depths of 100 feet, or somewhat more. Wells may also be *driven* in loose materials by forcing small metal tubes with perforated points to depths of 50 to 200 feet.

In hard bedrock formations, wells for water and oil are usually *drilled* by the percussion of a long, heavy steel weight which is raised and suddenly lowered repeatedly from a derrick, or by the more recently devised rotary method. Many wells have been drilled to depths of

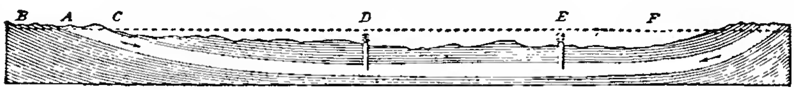



FIG. 188. Structure section illustrating flowing wells in a synclinal basin. (After U. S. Geological Survey.)

thousands of feet. Among several very deep wells in West Virginia, one showed a temperature of 172° F. at 7000 feet, and little or no water was encountered in it all the way down. A well over 7300 feet deep in southeastern Germany showed a temperature of 186° F. at the bottom. In 1938 a well 15,000 feet deep was drilled in southern California.

The drilling of deep wells, where samples of the rocks from different levels have been saved, has been an important aid to the geologist in rendering more precise a knowledge of the kinds, thicknesses, and structural relations of the rocks underground.

**Artesian Wells.** When a well, sunk to a porous water-bearing layer or formation, or a crack or fissure filled with water, encounters water under enough pressure to cause it to rise more or less in the hole, we have an *artesian well*. The water is often under a tremendous so-called "pressure head," but it may, or may not, flow out upon the earth's surface.

Requisite conditions for the most common type of artesian well are the following: a porous layer between water-tight layers; exposure of at least an edge of the porous layer so that water may enter it; inclination of the water-bearing layer (aquifer) so that the water will move downward in it under the action of gravity; absence of a ready escape of the water at a lower level than that of the well; and an adequate rainfall to furnish the supply of water.

An aquifer like that just described may extend under a valley, and outcrop on the hills on each side as shown by Figure 188; or it may be tilted in one direction and thin out, or grade into impervious material, as shown by Figure 189. In either case a flowing artesian well would be obtained by sinking a well through the upper water-tight layer into the aquifer. Some artesian basins are very extensive (Fig. 181), and

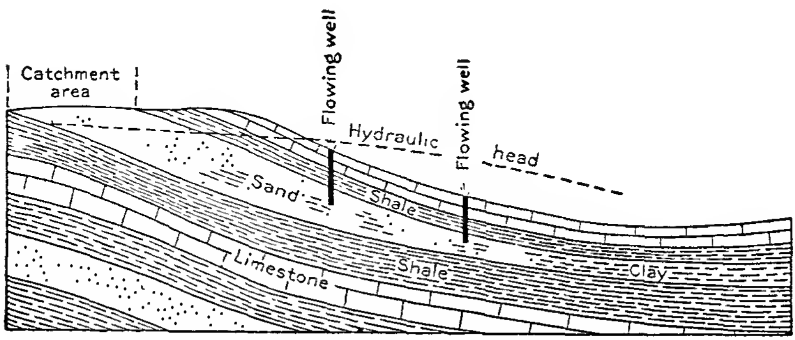



FIG. 189. Structure section illustrating flowing artesian wells in a monocline. (After U. S. Geological Survey.)

the water emerging from a well in such a basin may have traveled hundreds of miles underground.

If an aquifer, lying between water-tight beds, curves downward (synclinally) under a ridge, as shown by Figure 190, a well sunk to the aquifer from high up on the hill would be non-flowing, although the water might rise under great pressure to a considerable height in the hole. In none of the cases described will the water rise to the level of its source (or intake) because friction during the passage of the water through the porous rock layer reduces notably the pressure, the more so as the distance increases.

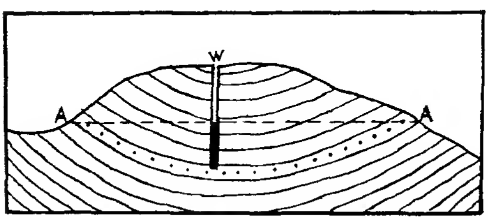



FIG. 190. Structure section illustrating a non-flowing well in a synclinal area. Dotted formation is the aquifier.

Much less commonly than the cases just mentioned, both flowing and non-flowing artesian wells may result where water is encountered under pressure in cracks, fissures, or channels in dense or hard rocks as suggested by Figure 191.

**Wells and Sanitation.** Fully two-thirds of the people of the United States depend upon wells for their water supply. Most of the people by far in the upper Mississippi Valley region use well water. The location of wells with reference to sanitary conditions is, therefore, of very great importance. Failure to give reasonable attention to simple, fundamental precautions is a reason for a large amount of sickness which could be avoided, especially in country districts.

Germ-laden water may travel surprisingly far underground. Water contaminated by barnyards, cesspools, and outhouses spreads notably on

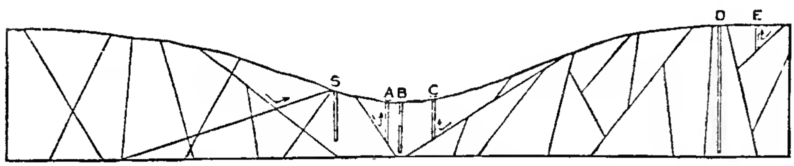



FIG. 191. Diagrammatic section showing springs and flowing wells in jointed rocks. (After U. S. Geological Survey.)

sinking to the water table in loose materials, often causing water in shallow (dug) wells close to houses and barns to become more or less germ-laden (Fig. 192). The safe well must be situated out of range of such contamination. Germ-laden surface water may also travel underground through fissures, cracks, or channels in bedrock, and contaminate wells and springs. Less often the surface, and near-surface, drainage may be down a hillside, while contaminated water may flow in the opposite direction underground in a porous layer of tilted bedrock. Even after a well has been carefully located in the light of the principles suggested, sanitary analyses of the water should be made once or twice a year to insure reasonable safety.

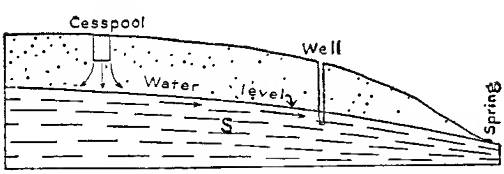



FIG. 192. Structure section showing one way by which wells and springs may be polluted. (After U. S. Geological Survey.)

## Work of Solution by Subsurface Water

**Solvent Action of Subsurface Water.** Mention has already been made of the fact that water begins to take more or less mineral matter into solution as soon as it enters the earth. Pure water has some power to dissolve mineral matter, but the carbonic acid gas, and other gases and acids, which it takes up from the air and from the decomposing organic matter in the soil, greatly increase its solvent power. If it moves downward far enough, it also becomes warm (or hot) and gets under pressure, thus making it a more powerful solvent. The most common rock which is readily soluble in such water is limestone, which consists largely, or wholly, of either calcite or dolomite. Gypsum and salt-bearing strata are readily attacked. Many other minerals, even as resistant as feldspar, also are taken at least partly into solution.

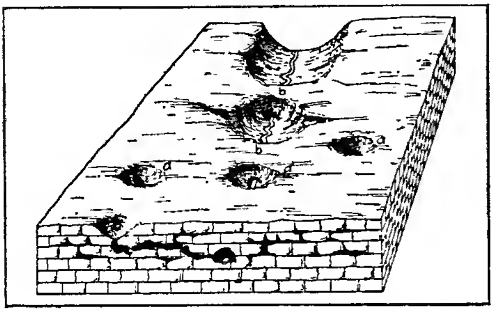



Fig. 193. Diagram illustrating the origin of caves (in black), sink holes (*a*), and natural bridges (*b*) in limestone. (After H. F. Cleland.)

**Amount of Material Dissolved.** One of two principal things may happen to mineral matter taken into solution by subsurface water. It is either carried deeper down into the zone of fracture and there deposited in openings in the rocks or it is brought to the surface, mainly through springs, to be carried to the sea by surface streams. The deposition of materials at lower levels is discussed beyond in this chapter. Even roughly approximate figures in regard to the amount of material deposited at lower levels in the zone of fracture cannot be given, but the quantity is certainly large. In the discussion of the rate of erosion of the United States, it is stated that, according to good estimates, the rivers of the country carry about 270,000,000 tons of dissolved mineral matter to the sea each year. Most of this enormous amount of material is taken into solution by underground waters within a few hundred feet of the surface, and fed into the streams through springs. Underground water, therefore, contributes notably to the general process of wearing down (erosion) of the lands, because the surface streams, as they cut down, have less rock material to remove.

**Caves, Sink Holes, and Natural Bridges Formed by Solution.** An important result of the solvent action of subsurface water, particularly in limestone regions, is the development of *caves* (or *caverns*). One of the most remarkable examples is Mammoth Cave, Kentucky. This wonderful work of nature is entirely the result of the action of underground water which has dissolved (and to some extent corraded) and carried away tremendous quantities of limestone. There are scores of miles of intricate passageways and galleries, some of them very large. A stream, called Echo River, aided by its tributaries, is still carrying on the work of solution, and so the cave is being enlarged. Among other famous large caverns similarly found in limestone are the recently discovered Carlsbad Cave, New Mexico; Oregon Caves, Oregon; Wind Cave, South Dakota; Wyandotte Cave, Indiana; and Luray Cave, Virginia.

An opening which connects a cave with the surface is called a *sink hole*. Sink holes may be formed either by the solvent action of surface water which finds its way into a cave, or by the collapse of part of the roof of a cave.

A *natural bridge* may be formed by the collapse of all but one portion of the roof of a cave. A famous example is the Natural Bridge of Virginia. Natural bridges are formed also in other ways, one of which is illustrated by Figure 117.

## Deposition by Subsurface Water

**Cave Deposits.** When water containing carbonic acid gas passes downward through a limy formation it becomes more or less lime-charged. A drop of such lime-charged water, on reaching the roof of a cave, evaporates somewhat, and gives up some of its gas, with the result that part of the lime is deposited. After hanging for a time on the ceiling, the drop of water falls to the floor where much, or all, of the remaining lime is deposited. Many repetitions of this process cause a long, slender, icicle-shaped incrustation of carbonate of lime, called a *stalactite*, to be built vertically downward from the roof of the cave, and a similar, though usually thicker, mass, called a *stalagmite*, to be built vertically upward from the floor. Many stalactites and stalagmites may form in a single cave, and some of them may join to form columns or pillars (Fig. 194). Wonderful and fantastic effects are thus often produced, dependent upon the manner in which the lime-charged waters trickle and spatter, as for example in the Luray Cave of Virginia; parts

of Mammoth Cave, Kentucky; and Wyandotte Cave, Indiana. Stalactites and stalagmites occur in great profusion, and of great size—5 to 25 feet in diameter, and 25 to 50 feet long—in the very recently explored Carlsbad Cave of New Mexico.

Under more exceptional conditions, stalactites and stalagmites may be formed of other minerals, such as chalcedony, limonite, etc. These

FIG. 194. Stalactites, stalagmites, and pillars in a cave. Oregon Caves, Oregon. (Photo by courtesy of the U. S. Forest Service.)

are rarer and usually much smaller than those of lime because the materials are more difficultly soluble.

**Spring Deposits.** When underground water, highly charged with mineral matter, reaches the surface as a spring, there is a strong tendency for it to deposit at least part of its mineral load. Reduction of pressure, lowering of temperature, and escape of carbonic acid gas, are among the principal factors which cause such deposition by springs (Fig. 187). Deposits of carbonate of lime are not uncommonly found around springs of even relatively cool water, where the mineral-charge is heavy. *Travertine* is a general name applied to limy spring deposits, while the more porous or stringy, limy masses are called *calcareous tufa*.

Large, hot springs are especially likely to yield extensive deposits

in their immediate vicinities, an excellent case in point being the great accumulations of travertine around the Mammoth Hot Springs of Yellowstone Park (Fig. 187). The alkaline waters of the hot springs and geysers of the Yellowstone geyser basins bring much so-called *geyserite* to the surface where it accumulates. This porous material is the same in composition as the mineral quartz. Other mineral substances are less often deposited by springs.

**Belt of Cementation; Veins.** Underground water accomplishes much of its work of solution in the upper portion of the zone of fracture, that is, in the belt of weathering. As the water moves downward, it becomes richer in mineral matter, and more sluggish. Ascending hot water, under high pressure, loses pressure and becomes cooler. The tendency is for the dissolved substances to be deposited under such conditions, filling cracks, fissures, and openings of all kinds, even exceedingly small ones. That portion of the zone of fracture, in which deposition of dissolved minerals takes place, is called the *belt of cementation*. Many sedimentary rocks are consolidated by cementation in this belt. Cracks and fissures filled with mineral matter from underground water solutions are called *veins* (Fig. 195). Among the very common vein-forming minerals are quartz, calcite, fluorite, and barite. Two or more minerals may occur in one vein. Where underground openings are filled only partly with mineral matter, beautiful crystals often occur.

FIG. 195. Veins of calcite in a pebble of schist.

Valuable ores, such as those of gold, silver, copper, lead, and zinc, usually have been deposited from underground water solutions, and concentrated in veins in many regions. Deposition also often results where underground waters with certain substances in solution travel through various rocks, or encounter solutions of other substances, thus bringing about chemical reactions which may develop insoluble substances, with resultant deposition of the latter.

Mineral-charged subsurface water may also bring about *petrifaction,* that is, the replacement, particle by particle, or cell by cell, of a buried shell, log, or other remains of an organism by the mineral matter from

FIG. 196. A petrified tree trunk partly exposed in volcanic fragmental rock. Ginkgo National Monument, Washington.

an underground solution. In this manner the so-called Petrified Forests of Arizona, of Yellowstone Park, and of other regions were formed, the petrifying material having been the very common substance called "silica," which is the same in composition as the mineral quartz.

# CHAPTER XIII

## MOUNTAINS, PLATEAUS, AND PLAINS

### Principal Relief Features of the Land

**General Statement.** Mountains constitute the most conspicuous relief features of the earth. The expression "everlasting hills" may seem appropriate to the layman who is impressed by the grandeur and massiveness of mountains. To the geologist, however, mountains, even the grandest of them, are known to be but transitory forms. A mountain, like an organism, has a life history which may be relatively short and simple, or long and complex. Many of the most profound lessons of geology have been learned from the study of the tilted, folded, faulted, and deeply eroded rocks of the earth's crust where they are exhibited so wonderfully in mountains.

**Definition of Mountains.** In the commonly accepted sense of the term, a mountain is any notably elevated portion of a region. As more precisely defined, "*mountains* are conspicuously high lands which have but slight summit areas" (R. D. Salisbury). Mountains are conspicuously high in a relative sense only, that is, they stand out boldly above their surroundings. Low mountains are often called *hills*, but the distinction between these two terms is often a relative matter, usually depending upon the region in which the elevations occur. Thus in a region of low relief like Iowa, elevations of only 100 to 300 feet are sometimes referred to as mountains (e.g. Mount Vernon, Iowa), while in other regions elevations of 1000 to 3000 feet may be called hills (e.g. Berkshire Hills, Massachusetts). As a rule, however, elevated masses lower than a few hundred feet are not called mountains, and those higher than about 1000 feet are not called hills.

**Definition of Plateaus.** Tracts of relatively high land with considerable summit, or near-summit, areas are called *plateaus*. They nearly always rise distinctly and rather abruptly above the surrounding country on at least one side. True plateaus rarely, if ever, merge into lowlands (plains). Plateaus are usually higher than plains, but they may be considerably lower, as for example the Piedmont Plateau of the eastern United States which is much lower than the Great Plains lying

just east of the Rocky Mountains. Plateau surfaces are usually more or less trenched by valleys, or even great canyons; and mountains rise above the general level of some of them.

An excellent large-scale example of a high-level plateau with a conspicuous descent on one side is the great Colorado Plateau of the southwestern United States (Fig. 1). It lies from 5000 to 11,000 feet above sea level, with a gradual increase in altitude from south to north, and it is separated from the Great Basin on the west by a steep slope (fault scarp) 1000 to 3000 feet high. It is trenched deeply by the Grand Canyon of Arizona.

**Definition of Plains.** Tracts of relatively low, level lands are called *plains*. In actual usage the terms "plains" and "plateaus" are often confused, and, as a matter of fact, a very clear distinction between them is difficult to make. Plains are, as a rule, lower than plateaus, but there are striking exceptions, as for example the Great Plains of the United States lying at altitudes of from 3000 to 6000 feet, and gradually descending eastward into the Interior Lowland (Fig. 1). Relation to the surrounding country is a more important criterion than altitude for distinguishing between plateaus and plains. Thus if the region known as the Great Plains were separated abruptly from the Interior Lowlands, or if it were almost surrounded by mountains, some such term as "Great Plateau" would be more appropriate.

Much of the continental areas are occupied by plains. Not only are plains the simplest of land forms, but also they are the most widespread. Most of the people of the world by far live upon plains. In the United States, plains are excellently and extensively illustrated by the Interior Lowland, the Great Plains, and the Atlantic and Gulf Coastal Plains (Fig. 1). The Great Plains are remarkably smooth, but the others mentioned are considerably trenched by stream-cut valleys.

## Arrangement of Mountains

A *mountain peak* is a more or less cone-shaped mountain mass, as for example Lassen Peak, Pike's Peak, Mt. Rainier, and Mt. Washington.

A *mountain ridge* is a relatively long, narrow mountain mass, such as the Blue Ridge and many others, often locally called mountains or ranges, in the Appalachian district.

Peaks or ridges, or both, may be grouped irregularly, as in the Adirondack and Catskill Mountains of New York. A single large

ridge may be surmounted by a number of peaks, as for example the Cascade Range. A single large ridge may be without very conspicuous peaks at its crest, as for example the Sierra Nevada Range. Many nearly parallel ridges may be grouped into long, relatively narrow belts, as in the case of the Appalachian Range.

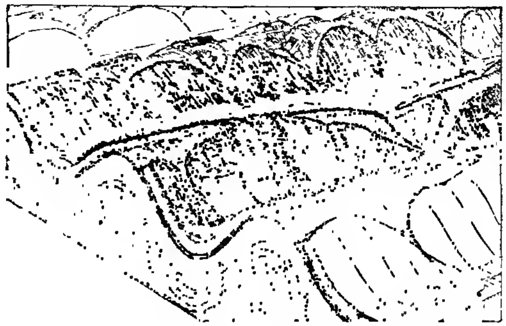


FIG. 197. Diagram and section showing slightly eroded, anticlinal, mountain ridges. Jura Mountains, Switzerland. (After W. M. Davis.)

A *mountain range* may, from the geological standpoint, best be regarded as a single mountain ridge, or group of ridges and peaks, often with more or less parallel arrangement, the material of which was built up into mountain form by a geological process (or set of processes) during a particular portion of geological time. In dealing with mountain origin and structure, the range is, therefore, a geological unit. The Appalachian Range, the Sierra Nevada Range, the Wasatch Range, the

FIG. 198. A mountain ridge carved out of vertical strata. West of Banff, Alberta Canada.

Coast Range, the Pyrenees, the Alps, and the Himalayas are good examples, though it should be borne in mind that most of these were rejuvenated after their original uplift.

A *mountain system* "consists of two or more mountain ranges, of the same (or nearly the same) period of origin, belonging to a common region of elevation, and generally either parallel, or in consecutive lines" (J. D. Dana). Thus the Laramide system includes a series of ranges in the Rocky Mountains.

A *mountain chain* consists of two or more systems or ranges formed at distinctly different geological times in a definite part of a continent, and usually more or less parallel. Thus the Appalachian Chain comprises the whole mountain region on the Atlantic side of North America, including the Acadian Range of Nova Scotia and New Brunswick, the mountains of eastern New England, the Green Mountains, the Berkshire Hills, the Highlands of the Hudson, and the Appalachian Range.

A *cordillera* is a grand combination of chains, systems, and ranges in one general portion of a continent. The North American Cordillera includes all the mountains from the eastern face of the Rocky Mountains to the Pacific Ocean.

## Origin of Mountains

**Folded Mountains.** *Character, origin, and structure of the materials.* Most of the great mountain ranges of the earth belong in the category of so-called *folded mountains.* Folding of strata, accompanied

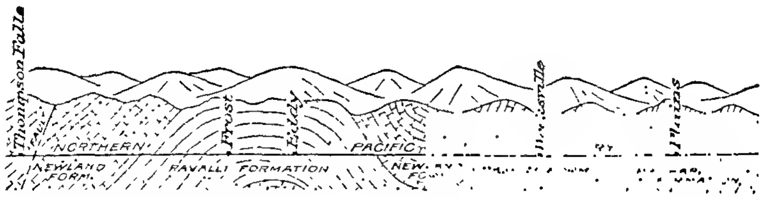



FIG. 199. Structure section 30 miles long showing deeply eroded folds. Rocky Mountains of Montana. (After U. S. Geological Survey.)

by general uplift, is the most important of the various modes of origin of mountains. A good idea of the general character, origin, and structure of the materials of a typical folded range may be gained from the consideration of a carefully studied example, such as the Appalachian Range.

Even a casual trip across the Appalachian Range would reveal the fact that the rock materials consist very largely of common kinds of stratified rocks, that is, sandstones, conglomerates, shales, and limestones. It would also be evident that the thickness of the strata must be measured by thousands of feet. As a matter of fact, careful determinations have shown that the strata of the Appalachians were deposited originally under water, layer upon layer, to a maximum thickness of 25,000 to 35,000 feet. The tremendous thickness of such a pile of strata clearly leads to the conclusion that the deposition must have continued for millions of years. Not only are the rocks of the Appalachians water-laid sediments of great thickness, but also they were deposited mostly under

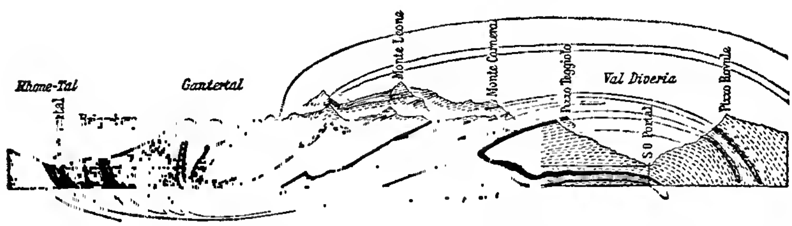



FIG. 200. Structure section showing the deeply eroded, very highly folded Alps along the line of the Simplon Tunnel. Length of section, 16 miles. (Kayser, after Heim.)

sea water as proved by the fact that they contain numerous fossil remains of typical marine animals.

The strata of a typical folded range, like the Appalachians, are largely, or wholly, of shallow-water origin, that is, they were laid down on the floor of a relatively shallow sea. This is proved by the very nature of the materials, particularly the sandstones and conglomerates; by the types of animals represented in fossil form; and by certain markings on many strata, such as ripple marks, mud cracks, etc. Since the strata are of shallow-water origin, and since they are piled up to a great thickness (many thousands of feet), it is obvious that the sea floor upon which the sediments accumulated must have subsided during the process of deposition. Such deposition of sediments usually takes place in a great down-warp, or subsiding trough, generally hundreds of miles long and 75 miles or more wide, known as a *geosyncline* to distinguish it from an ordinary syncline.

The folded strata of a typical folded range are nearly always arranged in relatively long, narrow belts or zones. This is because they consist

very largely of land-derived materials which were deposited in shallow water along the margin of a land area. This is in harmony with the well-known fact that, at the present time, land-derived sediments (gravel, sand, and mud) are deposited almost entirely within 100 to 200 miles of the continents. We must, therefore, think of the site of a typical folded range as once having been a subsiding, marginal sea bottom upon which sediments piled up layer upon layer for millions of years to a thickness of many thousands of feet.

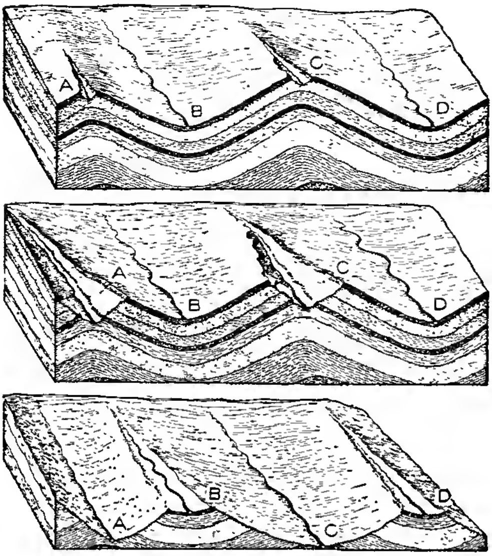



FIG. 201. Block diagrams showing how erosion may cause anticlinal valleys and synclinal mountains. (From Tarr's "New Physical Geography," by permission of the Macmillan Company.)

One of the most strikingly evident features of a typical folded range is that the strata are not in essential horizontal position as they were when they were deposited, but that they have been much disturbed and thrown into folds. Single folds range in length and width from less than a few feet to miles (Figs. 63 and 199). The degree of folding varies from gentle anticlinal and synclinal structures to overturned and recumbent folds, and even to compressed isoclinal folds (Figs. 56 and 60). Such folded structures were, as explained in Chapter VI, developed by a tremendous force of lateral compression within the zone of flowage of the earth's crust. The folds are now exposed as a result of removal of overlying material by subsequent erosion. The main axes of the folds, with some minor exceptions, extend essentially parallel to the main trend of a folded range. This is because the force of compression was exerted at right angles to the trend of the range.

A high degree of folding of strata results in a considerable amount of earth-crust shortening. This is because the belts of once horizontal strata are crumpled into much narrower zones. It has been estimated

that the crustal shortening caused by the Appalachian folding across southern Pennsylvania was fully 26 miles. In the very severely folded Alps the shortening is much greater.

*Brief history of a folded range.* In dealing with a cycle of erosion or topographic development, we used the terms infancy, youth, maturity, and old age. In a somewhat similar manner we may use a biological analogy in dealing with the evolution of a typical folded range. First there is the *embryonic stage* during which the sediments accumulate

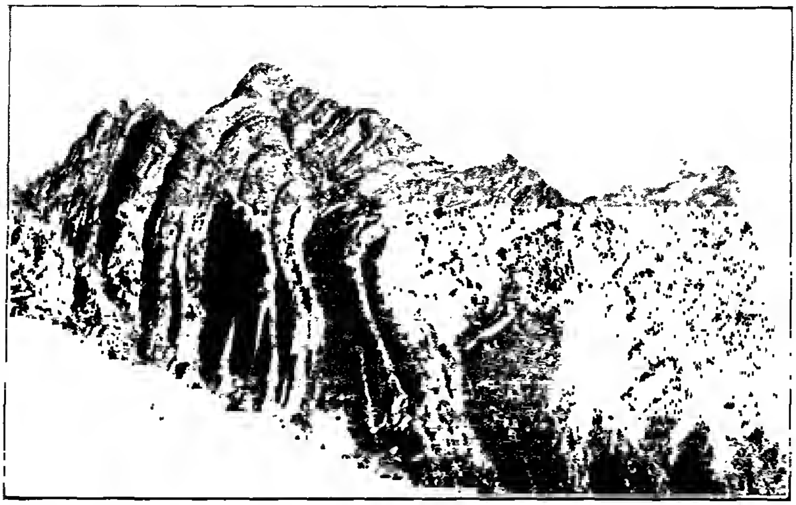


FIG. 202. A mountain ridge carved out of highly inclined, folded strata. Height of mountain, about 2000 feet. Heaven's Peak, Montana. (Photo by Chapman for U. S. Geological Survey.)

upon the marginal sea floor. This stage is usually very long—millions of years at least.

Next comes the *birth* of the range when the strata are subjected to lateral pressure, somewhat folded, and raised partly out of the sea.

During the *youthful stage* the mountain range grows, that is, it increases in altitude, and the folding becomes more complex, because the compressive force is still very active. The increase in height takes place because the constructive force of uplift is greater than the destructive force of erosion, which latter already operates to cut down the range.

The *mature stage* is reached when the upbuilding process is about equalled by the tearing down (erosive) process. It is during this stage

that the range exhibits its greatest altitude and its maximum ruggedness of relief.

During the *old-age stage,* the upbuilding process either greatly diminishes, or ceases altogether, and the tearing down process of erosion causes a steady reduction in the height of the range.

Finally the *extinction* of the range, as a conspicuous relief feature, is reached when erosion has reduced it to the condition of a peneplain.

The normal order of events in the history of a folded range, as above outlined, may be interrupted at any stage by renewal, or accentuation, of uplift, particularly after maturity, causing a revival of stream activity, and an increase in ruggedness of relief. Even after a range has been peneplaned it may be uplifted and rejuvenated with establishment of a new cycle of erosion. Subsidence would directly cause a lowering of the range and a slowing down of the process of erosion.

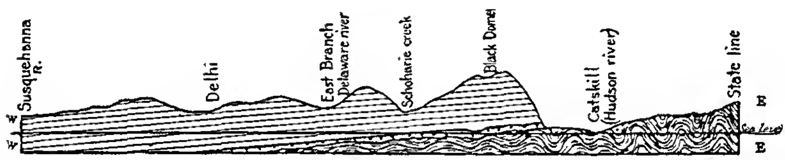



FIG. 203. Structure section illustrating the date of folding of strata. The folded rocks are Ordovician and older; the non-folded rocks are Silurian and Devonian. The folds were produced before the non-folded strata were deposited. Catskill Mountain region, New York.

*Rate and date of folding.* It must be clearly understood that folding and uplift of a great body of strata into a large mountain range is a very slow process, generally requiring hundreds of thousands, or even some millions, of years. As compared to the long eons of known geological time, the active process of folding does, however, take place within a comparatively short time. It is usually much less than the time necessary for the deposition of the strata. Great mountain ranges have been formed by folding of rocks at various times, and in many places, during geological time. Such mountain-making (orogenic) disturbances are commonly called "revolutions." Thus, in North America, since the opening of the Paleozoic era, some of the most important orogenic disturbances have been as follows: Taconic Revolution, in western New England and southeastern New York, at the close of Ordovician time (see table in Chapter I). Appalachian Revolution toward the close of the Paleozoic era; Sierra Nevada Revolution toward the close of the Jurassic period; Rocky Mountain Revolution toward the close of the

Cretaceous period; and the Coast Range Revolution at the close of the Tertiary period.

How is the date of a folded range determined? Two principles are involved. First, it is necessary to determine the geological age of the latest (youngest) strata involved in the folding. The folding must have occurred *after* the deposition of such strata. Second, it is necessary to determine the geological age of the oldest (lowest) non-folded, or less folded, strata resting (by unconformity) upon the folded rocks. The folding of the underlying rocks must have taken place *before* the deposition of the overlying strata (Fig. 203). To use a concrete example, we know that the Appalachian Revolution occurred at about the close of the Paleozoic era because the youngest folded strata are of very late Paleozoic age, while the oldest non-folded strata, resting upon the folded rocks, are of early Mesozoic age.

*Cause of folding.* We are reasonably certain that the earth does not consist of a molten interior covered by a solid crust but rather that it is composed of a great, hot, solid interior enveloped by a relatively cool, outer, or crustal, portion. Mountain-folding, with its accompanying crustal shortening, is quite certainly produced by lateral pressure within the earth's crust. It seems to be a well-established fact that the earth has been a shrinking body for long ages of geological time. It also seems to be clear that orogenic, or mountain-folding, forces are somehow caused by earth contraction with its resultant stresses and strains in the shell (or crust) of the earth.

**Faulted (Block) Mountains.** Many mountain ranges are caused either partly or wholly by faulting, whereby great earth blocks are made to stand out in relief. Such blocks are often tilted, and they

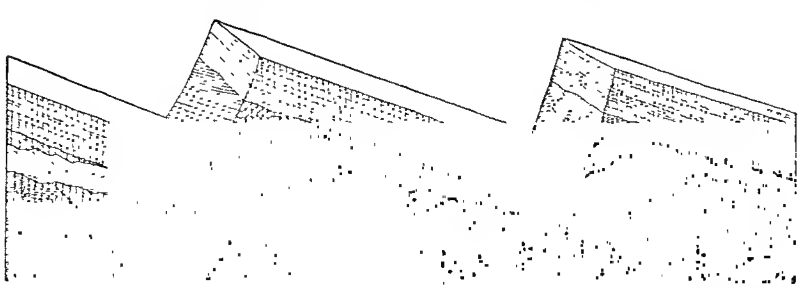


FIG. 204. Diagrams illustrating fault-block mountains. Horizontal strata were laid down upon the peneplained surface of strongly folded strata. Then a series of tilted block mountains developed, and the blocks were much modified by erosion and deposition. Back diagram represents the blocks in potential non-eroded form. (After W. M. Davis.)

are called *faulted* or *block mountains.* Tilted block mountains are developed typically in southeastern Oregon (Fig. 209) where a series of them from 10 to 40 miles long, and 1000 feet or more high, have their fault scarps affected only slightly by erosion. Many of the north-south ranges of Nevada and Utah are block mountains considerably modified by erosion. The bold western face of the Wasatch Range of Utah is a moderately eroded fault scarp about a mile high, and many miles long. Grandest of all in the United States, however, is the Sierra Nevada Range which is a single, great, tilted, fault block over 400 miles long, and from 60 to 75 miles wide. A somewhat eroded, very steep, fault scarp, ranging from a few thousand feet to two miles high, sharply bounds the range on the east side, while a long, relatively gradual slope forms its western side (Fig. 105). A portion of the Rhine

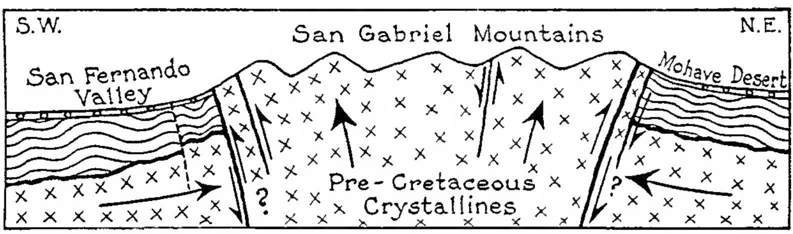



FIG. 205. Diagrammatic structure section to show how the western San Gabriel Mountains of California have been squeezed up as a fault block (horst). Arrows indicate directions of forces involved. The block of crystalline (igneous and metamorphic) rocks is flanked on each side by thick bodies of disturbed strata. Vertical scale is much exaggerated. Length of section about 55 miles.

Valley of Germany is a sunken fault block lying between two tilted fault blocks—the Vosges and the Black Forest. The San Gabriel Mountains of southern California constitute a good example of an earth-block which has been uplifted between two faults.

**Volcanic Mountains.** We have already learned that many mountain peaks, often of great height, have been built up by accumulations of igneous materials around the vents of volcanoes. Some of these are listed in Chapter XI.

Not only individual peaks, but also whole mountain ranges may be built largely, or wholly, by volcanic action. Thus the Cascade Range, extending for hundreds of miles from northern California through Oregon and Washington is, to a considerable extent, a volcanic mountain range whose once greatest centers of activity are marked by conspicuous

cones like Mounts Lassen, Shasta, Pitt, Hood, St. Helens, Rainier, and Baker. The chain of the Aleutian Islands of Alaska, more than a thousand miles long, is an excellent illustration of a mountain range now being built in the sea by active volcanoes. The Hawaiian Islands represent the highest parts of a great, largely submarine, volcanic range hundreds of miles long.

**Laccolithic Mountains.** Closely related to volcanic peaks in origin are so-called *laccolithic mountains,* the principle of which has al-

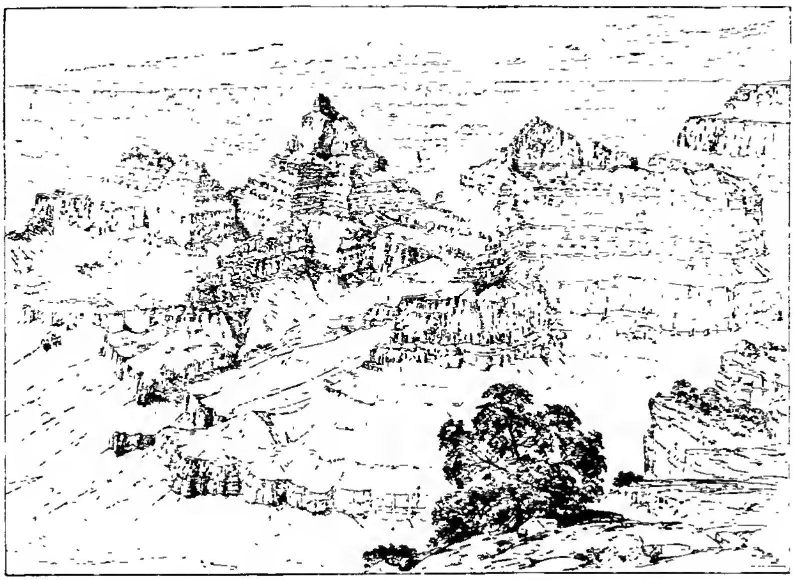


FIG. 206. Mountainous masses several thousand feet high carved out of nearly horizontal strata. Grand Canyon, Arizona. (After Holmes, U. S. Geological Survey.)

ready been described. In such cases molten material is forced into the crust of the earth, but instead of reaching the surface, it bulges or lifts the upper portion of the crust into dome-like forms. Laccoliths are very typically illustrated in southeastern Utah, and also in parts of Colorado, Wyoming, and South Dakota, in all of which regions practically horizontal strata have been bulged up by magmas. There they show all stages of erosion from those whose covers are practically intact to others whose igneous cores have been more or less laid bare, with the eroded edges of strata lapping up on their flanks (Fig. 83). Laccolithic moun-

tains are neither abundant nor very large. They occur singly, or in groups, but practically never in the form of distinct ranges.

**Erosion Mountains.** All mountains are of course subjected to, and modified by, erosion. In not a few cases, however, mountains may be developed by erosion alone in uplifted regions little, if any, affected by folding, faulting, or igneous activity. Such so-called *erosion mountains* are formed by the erosive sculpturing of plateaus and high plains into high ridges, peaks (or buttes), mesas, and deep valleys. The Catskill Mountains of New York, with their numerous narrow ridges and deep valleys, have been carved out of upraised, nearly horizontal strata simply by erosion. The maze of sharp mountain ridges and narrow valleys constituting the badlands of parts of Wyoming and South Dakota, have been eroded out of high, relatively soft, nearly horizontal strata. The numerous peaks and pinnacles which rise mountain-like within the Grand Canyon of Arizona (Fig. 206) are really erosion remnants, or erosion mountains. Another good illustration of erosion mountains is near the mouth of Zion Canyon, Utah, where mountain peaks several thousand feet high have been carved by erosion out of horizontal strata lying from 4000 to 8000 feet above sea level.

**Composite Mountains.** In addition to erosion which affects all mountains of whatsoever mode of origin, folding, faulting, and igneous activity may all play important parts in the development of a single mountain range. This was true of the Appalachian Range, especially its southern portion. The severe folding of the original Sierra Nevada Range was accompanied by tremendous intrusions of granite magma, as well as by vigorous erosion. Faulting and erosion only have entered into the development of the block mountains of southeastern Oregon. Many mountains are wholly of igneous origin, and more or less modified by erosion.

Various mountain ranges formed by folding have been deeply eroded, and then rejuvenated by uplift without notable folding or faulting. Examples of such rejuvenated ranges are given beyond.

## Sculpturing and Destruction of Mountains

From the very beginning of its history as a topographic feature, every mountain mass is attacked unceasingly by weathering and erosion which continue to operate during the periods of youth, maturity, and old

age. In the course of time every mountain will be leveled by erosion unless it is rejuvenated by some process of igneous activity or diastrophism. Cases of rejuvenation are described under the next heading.

All three of the great erosive agents—water, ice, and wind—are important in the sculpturing of mountains, but water is the most effective. The principles of weathering, and of water, ice, and wind erosion, as well as many topographic forms resulting from their action, are described in preceding chapters, and it seems unnecessary to repeat them here in their direct bearing upon mountain sculpturing. Some general effects of the action of running water will, however, be mentioned. Thus a range consisting of well-defined more or less parallel folds will, in maturity, or after rejuvenation, be eroded into a system of parallel ridges and valleys (e.g. the Appalachian Range.) A mountain mass consisting of approximately horizontal strata (e.g. the Catskill Mountains), or of igneous or metamorphic rocks without well-defined structures (e.g. the western Adirondack Mountains) will be carved into a maze of valleys and ridges. Conspicuous valleys will often develop along lines of prominent faults (e.g. the eastern Adirondacks, and the Coast Range Mountains). Volcanic and laccolithic peaks will be trenched deeply with valleys radiating from near their summits (e.g. Mt. Shasta). Block mountains will be dissected variously by erosion depending upon the attitude of the blocks, and the character and structure of their rocks. Great tilted blocks will, in youth and maturity, have a system of approximately parallel canyons carved out of their long, more gradual slopes, and short steep gorges and canyons in their fault scarps (e.g. the Sierra Nevada Range).

In cold, humid regions, mountains may be sculptured considerably by glaciers which cause development of U-shaped valleys, cirques, and knife-edge ridges (e.g. Glacier Park, Montana).

The action of wind is an erosive factor usually of considerable importance in mountains in arid regions (e.g. the Great Basin mountains of Nevada and Utah).

## Rejuvenation of Mountains

The history of many mountain ranges is more or less complex. A range may be born and pass through the mature and old-age stages to extinction (peneplain stage) practically without interruption. It may, or may not, then be rejuvenated by diastrophism or igneous activity. A

range may have its normal life history interrupted at some particular stage, or during more than one stage. The more the great ranges are being studied, the more it is realized that the life histories of many of them are by no means regular and simple. Two examples of interrupted cycles of mountain history will serve to make clear the general principles.

The Sierra Nevada Range was severely folded and elevated toward the close of the Jurassic period. Great volumes of granite magma were intruded at the same time. Erosion then held sway until the range

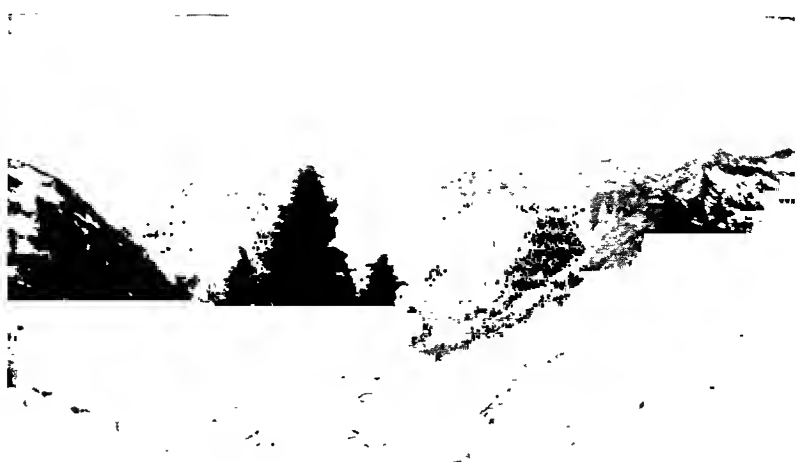


FIG. 207. A view in the Cascade Mountains. The plateau summit, marked by a nearly even sky-line, represents an old-age surface of base-leveled mountains which was uplifted thousands of feet and deeply cut into by streams. Gold Creek region of central Washington. (Photo by U. S. Geological Survey.)

was reduced to hills by later Tertiary time. Then a great fault fracture began to develop along the eastern side, and the whole Sierra Nevada fault block has been upraised and tilted into its present position. The many deep canyons, like Yosemite, Kern River, King's River, American River, and Feather River, have been cut into the western slope of the fault block by erosion.

The Appalachian Mountain district was subjected to several minor, more or less local, uplifts during the Paleozoic era, but the grand climax (Appalachian Revolution) of folding and uplift occurred toward the close of the era. Accompanying, and shortly following the

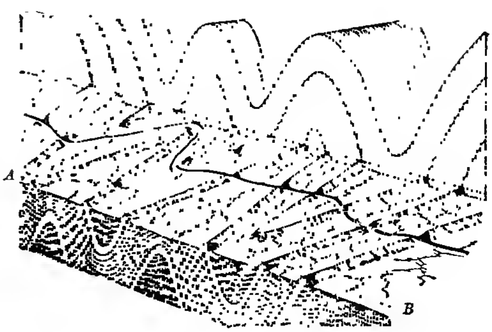



FIG. 208. Block diagram illustrating three stages in the history of the middle Appalachian region. 1, original folds as they would have appeared if unaffected by erosion; 2, peneplanation of mountains to surface AB; 3, rejuvenation of region and erosion to the present ridge-valley surface. (After W. M. Davis.)

folding, great thrust faults developed. Throughout Mesozoic time, the range was subjected to profound erosion, and reduced to the condition of a peneplain. About the middle of the present (Cenozoic) era, the whole peneplaned region was rejuvenated by irregular uplift and warping, but without real folding. The amount of uplift usually varied from 1000 feet to several thousand feet. The existing ruggedness of the range is due to erosion which has operated upon the rejuvenated range (Fig. 208). The system of long, narrow mountain ridges and valleys has been determined by the harder and softer rock formations which follow the strike of the original folds.

## ORIGIN AND HISTORY OF PLATEAUS

Some of the most important modes of origin of great plateaus are the following: (1) By simple uplift with little or no tilting, faulting, or folding, good examples being the plateau of southwestern New York, and the Allegheny Plateau just west of the Appalachian Range; (2) by uplift with tilting and some faulting, but with little or no folding, an excellent case in point being the great Colorado Plateau; and (3) by the upbuilding of a region by many outpourings of lava, as illustrated by the Columbia Plateau of the northwestern United States. Smaller plateaus (or table lands) may originate by being faulted above the surrounding country or by cutting down the surrounding country by erosion.

Plateaus, as well as mountains, are attacked by weathering and erosion from the very beginning of their history. By maturity, the original, more or less flat, surfaces are much trenched and dissected by erosion, giving rise to maximum ruggedness of relief. They are then often

called mountains (e.g. Catskill Mountains) instead of plateaus. With continued erosion, plateaus become more subdued in relief, and they are worn down finally to peneplains. As in the case of mountains, so with plateaus, the normal cycle of topographic development may be interrupted by rejuvenation.

## Origin and History of Plains

Extensive plains may originate by simple uplift accompanied by little or no tilting, warping, or folding. A good example is the wide Interior Plain of the Upper Mississippi Valley which is nearly everywhere less than 1000 feet above sea level, and considerably dissected by erosion.

Great plains may originate by uplift accompanied by notable tilting, as for example the Great Plains area which inclines downward, from an altitude of a mile or more at the base of the Rocky Mountains to a thousand feet or less, within a distance of several hundred miles eastward (Fig. 1). The Great Plains are affected relatively little by erosion.

Plains of great extent may be formed by emergence of a marginal sea bottom, without notable folding, faulting, or warping, either by uplift of the land, or by withdrawal of the sea, or by both. Wonderful examples are the Atlantic and Gulf Coastal Plains of the United States (Fig. 1). During the uplift, which was the prime factor in their production, these plains were tilted seaward. They have been dissected considerably by erosion, though many wide, smooth areas remain.

Wide plains which result from long-continued erosion of land areas are called peneplains. Many extensive peneplains are known to have developed during geological time, but good examples are rare at present because nearly all of those of fairly recent origin have been rejuvenated by uplift. Good examples of such upraised peneplains are those of the Appalachian and southern New England districts. Such uplifted peneplains are best classed among plateaus.

Glacial drift surfaces are often smooth enough for considerable distances to be called plains. A fine illustration is the broad, flat deposit left by the last ice sheet from central to northern Iowa.

Many relatively small plains are floors of extinct lakes which were built up and smoothed off either by deposition of sediment, or by mineral matter from solution. An exceptionally fine, large-scale example is the floor of the great glacial Lake Agassiz (p. 265).

Rivers form flood plains by deposition and lateral erosion, and delta plains by deposition.

Plains may be modified by erosion, diastrophism, vulcanism, or deposition of material. High, or steeply inclined, plains can be affected very profoundly by erosion. High plains, like mountains and plateaus, reach maximum ruggedness of relief during the mature stages of their erosional history. Low plains, by their very position, can be affected but little by erosion. It is an interesting fact that an extensive low-lying plain may last much longer without notable change than a great mountain range.

# CHAPTER XIV

## ORIGIN AND HISTORY OF LAKES

### General Features

A *lake* is an inland body of standing water. Either its water may be stationary, or it may have a moderate current through it. Lakes always occur where the surface drainage is obstructed. Two necessary conditions are basin-like depressions, and sufficient water to at least partly fill them. Lakes may consist of either fresh or salt water. Fresh-water lakes always have outlets. Some lakes are rather inappropriately called "seas," as for example the Dead Sea of Palestine.

Lakes vary in size from tiny ponds to sheets of water covering many thousands of square miles, though probably not more than a dozen in the world occupy areas of over 10,000 square miles. Largest of all is the Caspian Sea with an area of 169,000 square miles. The second largest is Lake Superior, covering nearly 31,000 square miles.

Lakes are known to vary in depth from a few inches to a maximum of 5618 feet in Lake Baikal of Siberia. The Caspian Sea has a depth of at least 3200 feet. Crater Lake, Oregon, with a depth of nearly 2000 feet, is probably the deepest lake in North America.

Most lakes by far lie above sea level at all altitudes up to many thousands of feet. A remarkable case is Lake Titicaca (area, 3200 square miles) in South America at an altitude of 12,875 feet. The highest large lake in the United States is Yellowstone Lake at 7741 feet. Lake Tahoe on the California-Nevada line lies at 6225 feet.

The surfaces of some large lakes lie below sea level, examples being the Dead Sea of Palestine (− 1300 feet), the Caspian Sea (− 85 feet), and the Salton Sea of California (− 249 feet).

The bottoms of a number of large lakes are well below sea level, a few examples being Lake Baikal (− 4000 feet or more), Lake Ontario (− 491 feet), Lake Chelan in Washington (− 421 feet), and Lake Superior (− 402 feet).

Most lakes in humid regions have surface outlets, that is, there is usually sufficient water to cause them to overflow the lowest parts of

their basin rims. Such lakes consist of fresh water. In arid regions lakes usually do not have outlets, both because of the scanty volume of water, and the high rate of evaporation. Many depressions in arid regions contain no water at all, while others, called *playas*, hold water only temporarily, that is, for greater or less periods after rains. Arid-region lakes with no outlets almost invariably contain salt (or alkaline) water.

As compared to the many millions of years of the known history of the earth, lakes, excepting possibly the largest and deepest ones, are short-lived, most of them exceedingly so. This is because they are merely temporary obstructions to drainage, and are soon destroyed by one or more of several processes as explained beyond in this chapter.

## Origin of Lake Basins

**Basins Formed by Diastrophism.** *By faulting.* When a block of the earth's crust sinks or rises relatively to an adjacent block through the process of faulting, a troughlike basin often results. There are many examples in the Great Basin region of the western United States. A small basin, now partly filled with water, formed in 1872 as a result of a sudden renewed movement of 20 to 30 feet along a fault near the


Fig. 209. Structure section illustrating the origin of lake basins by faulting. Abert and Warner Lakes, Oregon. (After Russell, U. S. Geological Survey.)

base of the Sierra Nevada Range in the Owens Valley of southeastern California. Abert and Warner lakes of southern Oregon are very typical cases of lakes in basins between tilted fault blocks (Fig. 209).

In other cases, a block of earth bounded by two normal faults may have been depressed notably between two adjacent land masses, giving rise to a trough-fault basin. An excellent case in point is the basin in the bottom of which lies Lake Tahoe on the California-Nevada line (Fig. 210). The earth block settled several thousand feet to form the basin. The lake is 22 miles long, and 12 miles wide. Its surface lies 6225 feet above sea level. It has a depth of at least 1645 feet, making it one of the few deepest lakes in North America. Its water is remarkably clear and fresh, with an outlet through Truckee River.

Other remarkable examples of fault-basin lakes are Great Salt Lake, Utah, and Dead Sea, Palestine.

*By warping.* Warping of the earth's crust through differential movement also has caused the development of lake basins. Part of a river valley may be sufficiently upwarped to act as a dam, causing ponding of the water. Among examples ascribed to such a cause are the basin of Lake Geneva in Switzerland, and of Lake Timiskaming in Ontario, Canada. Among other large lake basins, which at least in part owe

Fig. 210. A view across Lake Tahoe from the Nevada side to California. (Photo by courtesy of Tavern Studio, Tahoe, California.)

their existence to warping, are those of the Great Lakes described beyond.

*By simple uplift.* When a portion of the sea bottom is raised into land, without faulting or notable warping, there often are shallow, irregular, basin-like depressions filled with water. The water is at first salty, but, in humid climates, it soon gives way to fresh water. A number of the lakes of the southern half of Florida, and of the plains of Siberia, are believed to be of this origin. Such lakes are very short-lived, because of their shallowness.

**Basins Formed by Vulcanism.** *Crater lakes.* Numerous lake basins are direct results of volcanic activity. Many of them are simply craters of inactive volcanoes more or less filled with water. Sometimes there are groups of such crater lakes, as in the Auvergne district of

France, the Eifel region of Germany, and the vicinity of Rome, Italy. These are all small, but beautiful, lakes.

Many crater lakes also occur in large and small craters of volcanoes in the western United States. Most remarkable of all is Crater Lake in the Cascade Mountains of southern Oregon (Fig. 211). It partly fills a vast hole (caldera), six miles in diameter, which resulted either from the collapse and subsidence of the upper portion of a once much higher volcanic cone, or from stupendous explosive activity.

FIG. 211. A view across Crater Lake, Oregon, showing Wizard Island—a recent cinder cone. (Photo by courtesy of the Southern Pacific Lines.)

The lake is nearly 2000 feet deep, being probably the deepest in North America. Its surface lies nearly 6200 feet above the sea. Great precipitous walls of rock completely encircle the lake. It has no surface outlet, and yet its water is fresh, probably in part because some of its water may leave by underground passages, and in part because no stream flows into it. The water supply is maintained by rainfall and snowfall.

*Lava-dam lakes.* Streams of molten lava may flow across valleys and there cool to form natural dams, causing the valley waters to be

ponded. Thus a great flow of lava from Skaptar Jökull, Iceland, in 1783, blocked a large river and a number of its tributaries, with resultant development of lakes.

The famous Sea of Galilee in Palestine was formed by a stream of lava which, in very recent geological time, flowed into and across the Jordan Valley, causing the River Jordan to be ponded nearly 700 feet below sea level. The water is fresh because the river flows through the lake.

A number of lava-dam lakes occur in the Sierra Nevada and Cascade Mountains of the western United States. An interesting example is Snag Lake in Lassen Volcanic Park, California, whose water level is

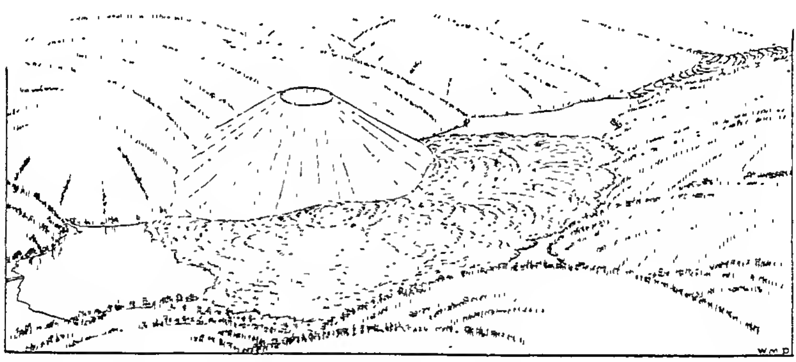


FIG. 212. A sketch showing how a lava flow, at the base of a cinder cone, poured across a lake-filled valley, leaving a part of the lake at each end of the flow. This kind of thing happened in Lassen Volcanic National Park. After W. M. Davis.)

held up by the very recent flow of lava already described as partly filling a valley (Fig. 212).

**Basins Formed by Glacial Action.** *By glacial-drift dams.* Lake basins formed by various processes of glaciation are more abundant than those formed in any other way. Of these, most by far have resulted from the deposition of glacial débris (moraines) in such manner as to obstruct the drainage of valleys. Many of the 8000 or more lakes in Minnesota, of the thousands in Wisconsin, and of the thousands in New York and New England belong in this category.

Lake Chelan in the Cascade Mountains of Washington is, in regard to length, depth, narrowness, and scenic setting, probably the most remarkable mountain lake of the United States. It is 60 miles long, less than two miles wide, about 1500 feet deep, and set in a winding moun-

tain canyon several thousand feet deep. First a river carved out most of the canyon. Then great floods of lava dammed its lower end, forming a lake. Finally a great valley glacier plowed through the basin, deepening it, and leaving a heavy morainic accumulation across its lower end, thus still further building up the dam. The present lake water is, therefore, held in place by a combination lava dam and glacial morainic dam.

*By ice dams.* Glaciers may blockade valleys, and thus cause ponding of waters. Lakes of this kind occur in Greenland, Alaska, and the Alps. An example is a small lake formed where the Great Aletsch Glacier in the Alps slowly flows past the mouth of a tributary valley,

FIG. 213. **A lake formed by blockading a valley with a morainic dam.** Blue Mountain Lake, New York.

causing a ponding of water in the latter. A great glacier flows into the Copper River of Alaska, ponding the water there.

Existing ice-dam lakes are not common, and few, if any of them, are large. During the Ice Age, however, thousands of them formed and lasted only as long as the ice dams existed. Some of them were of vast extent, vaster in fact than any existing lakes, with the possible exception of the Caspian Sea.

One of the largest of all known ice-dam lakes has been named Lake Agassiz. It occupied the Red River Valley region of Manitoba (including Lake Winnipeg), North Dakota, and Minnesota. It attained a maximum length of about 700 miles, and a width of over 200 miles,

when it covered 110,000 square miles, or considerably more territory than all of the Great Lakes. The lake formed because the northward drainage into Hudson Bay was blocked by the front of the retreating ice sheet during a late stage of the Ice Age. The outlet of this vast lake was southward into the Mississippi.

The Great Lakes constitute the most remarkable chain of big lakes in the world. They cover about 95,000 square miles. Various stages in the history of the Great Lakes developed along the retreating front of the great ice sheet during a late stage of the Ice Age.

FIG. 214. A rock-basin glacial lake. Lake Ellen Wilson, Glacier Park, Montana. (Copyright photo by R. E. Marble.)

*By glacial erosion.* A considerable number of glacial lake basins have been eroded or excavated by the direct action of flowing ice. Small *rock-basin lakes* of this kind, usually not more than ponds, often occur in the bottoms of the cirque basins at the heads of valleys formerly occupied by valley glaciers, because the excavating power of such glaciers was there especially effective. Less often, rock basins have been excavated by glaciers farther down their valleys. Valley-glacier, rock-basin lakes are numerous in parts of the Sierra Nevada, Cascade, and Rocky Mountains (Fig. 214), and also in the high mountains of Europe.

Other rock basins, including some large ones, were produced by the erosive action of the great ice sheets during the Ice Age. Some of numerous lake basins of Ontario, Canada, quite certainly belong in this category.

Many glacial lake basins owe their existence to a combination of erosion and deposition. The Great Lakes basins have already been men-

tioned as belonging in this category. Among many others are the Finger Lakes which form a remarkable group in central-western New York.

*By irregular deposition of glacial drift.* Many ponds and small lakes occupy depressions which have resulted from irregular deposition of glacial débris (drift). Such basins are merely depressions in the surface of the drift. They are common in the upper Mississippi Valley, New York, and New England, especially in association with the many recessional moraines. They differ from typical morainic dam basins not only in that they are completely surrounded by drift, but also in that they very commonly developed on flat, or only slightly hilly, land.

Ponds and small lakes may occupy depressions formed by the melting of large, isolated blocks of ice which have become buried under sediments. Masses of ice detached from a glacier may have been covered by morainic material left by the ice; or such masses may have been buried under material washed from the glacier (as in valley trains and outwash plains); or icebergs stranded in glacial lakes may have been buried under sediments carried into the lakes by streams. Ponds and lakes in such depressions are called *pit* or *kettle lakes.* They are most strikingly shown on otherwise nearly level, loose, extensive deposits which mark the sites of former glacial lakes. When such a surface is characterized by many kettle holes, some with and some without water, it is called a *pitted plain.*

**Basins Formed by Stream Action.** *By flood plain development.* We have already learned that graded and nearly graded rivers tend to wander in meandering loops over their flood plains, and that the necks of such loops are often cut across, leaving *oxbow lakes* like those so wonderfully exhibited on the flood plain of the lower Mississippi River.

Shallow basins often result from uneven deposition of the flood-plain sediments, especially in the spaces between the natural levees of the main streams and their tributaries.

*By delta growth.* As a result of uneven deposition of sediment by the network of distributaries on a delta, certain shallow basins are completely surrounded by the deposits, and thus converted into so-called *delta lakes.* A fine large-scale example is Lake Pontchartrain in Louisiana.

*By alluvial cones.* An alluvial cone or fan formed by a tributary stream may be built far enough out into its main stream (or valley) to obstruct the drainage of the latter, causing a ponding of the water. A good case in point is Lake Pepin which lies between Minnesota and Wisconsin. Much sediment carried by the Chippewa River into the Mississippi has there caused a ponding of the latter.

*By raft blockades.* Mention should be made of stream obstruction and deflection caused by so-called *rafts* or *jams* of trees and logs formed in rivers. The growth of such a raft upstream for many miles in the Red River of Louisiana so obstructed its tributaries as to develop a remarkable series of small and large lakes along them.

*By waterfall erosion.* Small lakes are sometimes found in abandoned stream courses, particularly where waterfalls have excavated so-called "plunge basins" at their bases. Fine examples of *plunge-basin lakes* are Jamesville Lake near Syracuse, New York, and near Coulee City, Washington, where large rivers once flowed.

**Basins Formed in Other Ways.** Brief mention will be made of some of the other modes of origin of lake basins, with examples.

*By waves and shore currents.* When the mouths of embayments of either sea or lakes are closed by the growth of bars or barriers through the action of either shore currents or waves, or both together, lakes result. Many examples occur along the Atlantic Coast from Long Island southward, and also around the borders of the Great Lakes.

*By wind.* Wind action often piles the materials of bars and barriers higher, thus causing them to be more effective dams where they close embayments of sea or lakes. Wind-blown sand may block streams locally, causing ponding of their waters. This has often happened along the southwestern coast of France. Depressions in sand dune areas sometimes contain water. Wind erosion may, under exceptional conditions, excavate basins in soft rock materials, as in parts of Argentina.

*By solution.* When sink holes are sufficiently obstructed by rock débris at their bottoms they may contain ponds or small lakes. Good examples occur in the northern half of Florida, and in Kentucky.

*By landslides.* Lakes are sometimes formed where landslides obstruct the drainage in valleys and canyons, particularly in regions of high relief. A good example is in the Kern River Canyon of the southern Sierra Nevada Mountains. In 1892 a great landslide blockaded the upper Ganges River in India, causing a lake five miles long and hundreds of feet deep. The lake disappeared in about two years by a giving way of the dam.

## Salt Lakes

**Origin of Salt Lakes.** Salt lakes are far less common than fresh lakes. They never have outlets. They almost invariably exist in arid regions, particularly in *interior drainage* regions, like the Great Basin area of the western United States, from which no streams flow into the

sea. In such regions the intake (precipitation and inflow) is often not sufficient to cause the lakes to overflow the lowest points of their basins to form outlets. With increase in dryness of climate, a fresh lake may, therefore, become a salt lake because the outlet is sooner or later abandoned, and mineral matter, carried in by streams, steadily accumulates in the water. Great Salt Lake, Utah, is one of the best-known examples belonging in this category. A salt lake may, under certain conditions, become a fresh lake. Thus Lake Champlain, which became detached from the Gulf of St. Lawrence by uplift of the land was a salt lake at first, but the salt has since been rinsed out through the outlet stream. Such a body of water, which was once connected with the sea, is called a *relic lake*.

Salt lakes may, in short, be formed in two ways, namely, (1) by accumulation of saline matter in lakes with no outlets, and (2) by cutting off arms of the sea either by diastrophism or by deposition of sediment, particularly in the form of a delta. Examples illustrating these principles will now be briefly described.

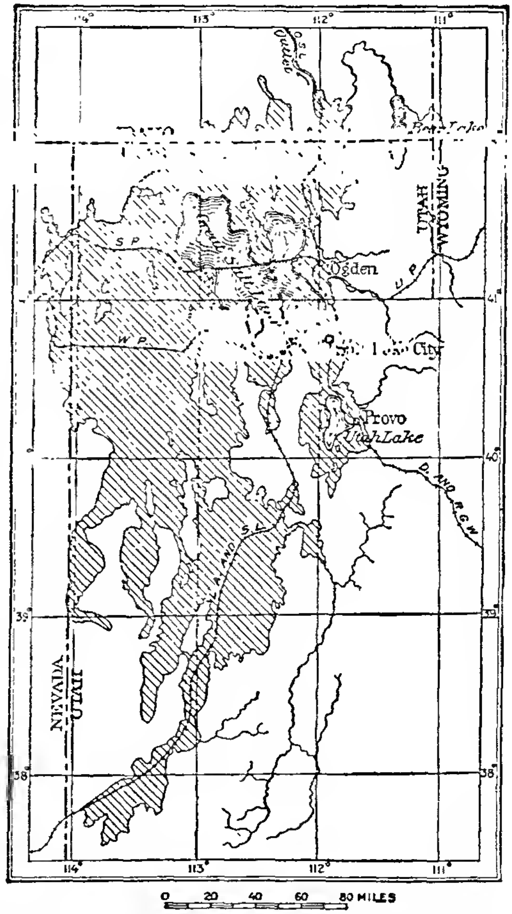



Fig. 215. Map of Great Salt Lake and its vast fresh-water ancestor, called Lake Bonneville (shaded). (After U. S. Geological Survey.)

**Examples of Salt Lakes.** Great Salt Lake, Utah, is a fine example of a salt lake not only whose saline matter has accumulated by concentration through excessive evaporation, but also whose ancestor was a fresh lake. As al-

ready mentioned, it occupies the lowest portion of the surface of a vast downsunken fault block in the Great Basin region. It covers nearly 2000 square miles, and its surface lies 4200 feet above sea level. It is remarkably shallow, the greatest depth being only about 40 feet. It is nearly five times as salty as the ocean, that is, it carries about eighteen per cent of saline matter in solution. It contains several billions of tons of common table salt, and hundreds of millions of tons of salts of soda, magnesia, potash, lime, etc. Very briefly stated, the history of the lake is as follows: when the climate was moister, the vast

FIG. 216. Lake Bonneville shorelines on the Oquirrh Range west of Salt Lake City, Utah. Successively lower terraces were formed by wave action during the lowering of the lake. (After G. K. Gilbert, U. S. Geological Survey.)

basin, now only partly occupied by the lake, was filled to overflowing with fresh water (Fig. 215). This great lake, called Lake Bonneville, was about two-thirds the size of Lake Superior, and its outlet was northward into the Snake-Columbia rivers. Lake Bonneville had a maximum depth of over 1000 feet. As the climate became drier, evaporation exceeded intake, and the outlet was abandoned. The water level fell, though not uniformly, and the lake became more and more salty by concentration of saline matter carried in by streams. Great Salt Lake is but a shrunken remnant of its vast ancestor. Many shoreline features, such as bars, beaches, deltas, and wave-cut cliffs, marking

various levels of the lowering waters of Lake Bonneville, are wonderfully preserved around the sides of the basin (Fig. 216).

The Dead Sea of Palestine lies in the lowest portion of the Jordan Valley which was formed by the sinking of a long, narrow block of the earth's crust between two nearly vertical, parallel faults. It covers an area of about 500 square miles; its greatest depth is about 1300 feet; and its surface lies about 1300 feet below sea level, making it the lowest lake in the world. Approximately 24 per cent of salts, chiefly chloride of magnesia and common salt, are in solution in its water. The Dead Sea is but a remnant of a once much larger (fresh-water) lake which had an outlet to the south. As the climate became drier, excessive evaporation caused the water level to lower more than a thousand feet, that is, to the present level of the Dead Sea. The salts in solution have been concentrated from the fresh water brought in by the streams, especially by the Jordan River.

## Destruction of Lakes

**By Filling with Sediments.** This is one of the most important methods of lake destruction. Some one has said that "rivers are the mortal enemies of lakes." All surface waters, especially streams, flowing into lakes carry more or less sediment with them. Most of the

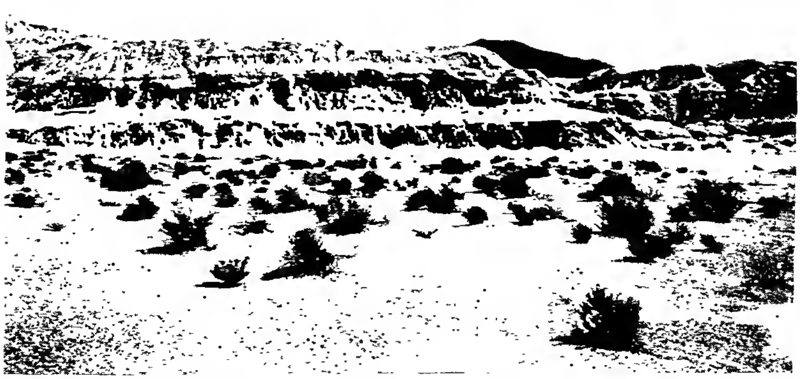


Fig. 217. Horizontal beds of clay which were deposited in a large lake hundreds of feet deep. The lake evaporated to a briny residue in the bottom of the desert basin. Searles Lake Basin, California.

sediment accumulates on the floors of the lakes because the latter are such excellent settling basins as already explained. Lake basins may, by this process alone, be completely filled, and the lakes destroyed.

Many lakes, particularly those of arid regions, receive more or less wind-blown sediment. In not a few cases extensive accumulations of volcanic dust have formed in lakes.

The materials eroded by waves along lake shores are mostly deposited in the lakes. Although such erosion enlarges the areas of lake basins, nevertheless their waters are, on the average, steadily made shallower because most of the material eroded and deposited comes from well above the lake levels.

**By Filling with Organic Remains.** In humid, temperate-climate regions, many small lakes have been, and are being destroyed by accumulations of vegetable matter, shells, etc. Plants usually grow in great profusion in the shallow, border portions of lakes. As the plants die their remains accumulate to form bogs which, in many cases, have encroached from all sides until lakes have been completely filled. Thousands of old lake bogs occur in New England, Wisconsin, and Minnesota.

Certain plants and animals secrete shells of carbonate of lime, and others, like single-celled diatoms, secrete shells of silica. In many lakes these shells are deposited to such an extent as to appreciably aid in lake-filling.

**By Cutting Down Outlets.** The dams of many lakes, particularly those formed of glacial débris, often consist of such loose, incoherent materials that outlet streams readily cut down into them. By this process, a lake surface may be reduced steadily until the lowest level of the lake basin is reached, causing destruction of the lake. Cutting down of outlets has been an important factor in the destruction of many lakes, especially of glacial lakes in regions like New England, New York, Wisconsin, and Minnesota. Of course it should be borne in mind that cutting down of outlets, filling with sediment, and filling with organic remains may proceed simultaneously.

Where the dams consist of relatively hard rocks, cutting down of outlets proceeds very slowly because outlet streams are usually very clear water whose erosive power is slight. This is true even of large rivers like Niagara and the St. Lawrence which have scarcely lowered the surfaces of the lakes they drain.

**By Removal of Ice Dams.** This principle is illustrated in certain regions of existing glaciers, as in the Alps, where a glacier, causing

ponding of water by blockading a tributary valley, may shift position in such a manner as to allow escape of the water either under or alongside the ice.

Many ice-dam lakes, including some of great size, were either completely, or largely destroyed by melting of their dams during the closing stages of the Ice Age. The once vast Lake Agassiz (already described) was destroyed in a similar manner, only remnants being left (e.g. Lake Winnipeg).

**By Evaporation.** This is a very important method of lake destruction in arid regions where evaporation may exceed intake. Many of

FIG. 218. An extensive field of rough, dirty salt left in a desert basin below sea level after a lake evaporated. Bottom of Death Valley, California.

the depressions in the Great Basin region which once contained lakes are now dry, or nearly so (e.g. Death Valley). Others now contain only small remnants of once large bodies of water, as for example the great basin of Lake Lahontan in western Nevada with its Pyramid Lake.

**By Diastrophism.** Ponds and small lakes are sometimes drained through fissures which are formed during earthquake disturbances. Lakes, especially larger ones, may be partly or wholly destroyed by down-warping or down-faulting of their outlet areas, but actual examples seem to be rare. It has been recently advocated that the great

post-Glacial lake which once lay in the Connecticut Valley of New England disappeared by down-warping of its outlet region.

## Extinct Lakes

We have just explained the most common ways by which lakes are destroyed, and cited some examples. Among the more important criteria by which the sites of former lakes may be recognized are the following: (1) If a lake basin has been completely filled, and since then little affected by erosion, its site is marked by a flat consisting of characteristic lake deposits, practically free from boulders. Such deposits may be sediments, organic (bog) materials, or salt-lake mineral deposits.

(2) Basins of larger ponds and lakes, which were not completely filled, very commonly show deposits of coarser sediments, usually in deltas and coalesced deltas, around their borders, and finer sediments, such as clays, farther out. The border deposits rise everywhere uniformly, unless subsequently affected by diastrophism, to about the former levels of the standing waters, while the finer sediments lie at various lower levels, depending upon the topography of the lake floors.

(3) In contrast with stream deposits, lake sediments (especially the finer materials) are usually much more uniform in character and structure over wide areas.

(4) In addition to deltas, other shore features, such as wave-cut cliffs, beaches, spits, and bars, are often wonderfully preserved. This is particularly true in arid regions, as around the shores of former Lake Bonneville, Utah (Fig. 216), but they are also often well exhibited in humid regions, as around the shores of the once great Lake Agassiz.

(5) Fossils often prove that deposits were formed in lakes because many forms of life in lake waters are characteristically different from those of sea water.

# PART II. HISTORICAL GEOLOGY

## CHAPTER XV

## GENERAL PRINCIPLES

### What Historical Geology Teaches

Historical geology deals with the records of events of earth history and with the history and evolution of plants and animals of past ages. Its object is to arrange the events of earth history in the regular order of their occurrence and to interpret their significance. The historical records are preserved in the rocks of the crust of the earth, the layers (or strata) of which have been likened to the leaves of a great book. At many places the pages of this vast "nature book" contain remarkable records and illustrations, while at others they are comparatively barren. As a result of the work of many able students of geology during the last century and a half, it has become a thoroughly established fact that our planet has a definitely recorded history running through hundreds of millions of years, and that, during the lapse of those eons, many revolutionary changes in earth features have occurred, and also that there has been a vast succession of living things which, from very early known time, have gradually evolved from simple to more and more complex forms. Here, as in all nature, ceaseless change is a cardinal principle.

In order that the reader may at the outset form a better general idea of the scope and nature of the subject, the following summary of some of the more important conclusions derived from the study of earth history is here presented.

1. *The age of the earth must be measured by hundreds of millions of years.*

2. *The physical geography of the earth has undergone many great and small changes during geological time.*

3. *All, or nearly all, of the surface of the lithosphere has at some time, or times, been covered by sea water.*

4. *The continents were roughly outlined in early geologic time.*

5. *During geologic time there has been a general tendency for the continental masses to become higher and grander.*

6. *Organisms inhabited the earth hundreds of millions of years ago.*

7. *Life once started has never ceased to exist.*

8. *Throughout the known history of the earth organisms have continuously changed.*

9. *The change in organisms has been progressive.*

10. *The evolution of life has not been uniform.*

11. *No species once extinct has ever reappeared.*

12. *While higher and higher types have been developed during geologic time, many of the earlier and simpler types have persisted.*

13. *The broader or larger biological groups of organisms have persisted longer than the smaller.*

14. *The life history of the individual tends to recapitulate the evolution or history of the race.*

## Fossils and Their Significance

Traces or remains of plants and animals preserved in the rocks are known as fossils. The term originally referred to anything dug out of the earth, whether organic or inorganic, but for many years it has been strictly applied to organisms. Paleontology, which literally means "science of ancient life," deals primarily with fossils.

Though many thousands of species of fossils have been described from rocks of all ages except the very oldest, and more are constantly being brought to light, it must be evident that, even where conditions of fossilization were most favorable, only a small part of the life of any period is represented by its fossils. Comparatively few remains of organisms now inhabiting the earth are being deposited under conditions favorable for their preservation as fossils. So it has been throughout the long periods of earth history, though the fossils in the rocks known and unknown are a fair average of the groups of organisms to which they belong.

**Preservation of Fossils.** 1. *Preservation of the entire organism by freezing.* Fossilization by this method is rare, though remarkable examples are afforded by extinct species of the mammoths and rhinoceroses, the bodies of which, with flesh, hide, and hair intact, have been found in frozen soils in Siberia.

2. *Preservation of only the hard parts of the organisms.* This is a very common kind of fossilization in which the soft parts have disap-

peared by decomposition, while the hard parts, such as bones, shells, etc. remain. Fossils of this kind are abundant in rocks of later geological time, though original shell material is frequently found, even in very ancient rocks.

3. *Preservation of carbon only (carbonization).* This is particularly true of plants where, as a result of slow chemical change or decomposition, the hydrogen and oxygen mostly disappear, leaving much of the carbon, but with the original structure often beautifully preserved. Many excellent examples are furnished by the fossil plants of the great coal (Pennsylvanian) age.

4. *Preservation of original form only (casts and molds).* Fossils of this class, which are very abundant, show none of the original material, but only the shape or form has been preserved. When a fossil becomes embedded in material, which hardens around the entire organism or any part of it, and the organism then decomposes or dissolves away, a cavity only is left and this is called a mold. Fine examples are the perfectly preserved insect molds in the famous amber of the Baltic Sea region. This amber is a hardened resin, the insects having been caught in it while it was still soft and exuding from the trees millions of years ago. Since then the insect material has almost completely dried away, leaving the molds. A cast may be formed by filling a mold with some substance such as sediment or mineral matter carried by under ground water, or by filling a hollow organism like a shell with some solid substance. The cast reproduces the internal form of the shell or organism.

5. *Preservation of original form and structure (petrifaction).* When a plant or hard part of an animal has been replaced, particle by particle, by mineral matter, we have what is called petrifaction. Often organic matter, such as wood, or inorganic matter, such as carbonate-of-lime shell, have been so perfectly replaced that the original minute structures are preserved as in life.

6. *Preservation of tracks of animals.* Footprints of animals, made in moderately soft mud or sandy mud which soon hardens and becomes covered with more sediment, are especially favorable for preservation.

**Rocks in which Fossils Occur.** 1. *Land deposits.* Old soils, peat-bogs, cave deposits, wind-blown materials, and even interglacial deposits often contain fossils. Lavas rarely contain fossils, but volcanic ash deposited in water may be rich in organic remains.

2. *River and lake deposits.* River deposits often carry river forms themselves, or land forms which fell into the stream and became en-

tombed in its deposits. Lakes offer very favorable conditions for fossilization.

3. *Marine deposits.* By far the largest number and variety of organic remains are found in rocks of marine origin, because on the sea bottom the conditions for their preservation have been most favorable. The distribution of fossils in strata of marine origin is, however, exceedingly irregular, ranging from those strata which are almost entirely made up of fossils to others which are nearly barren. Many conditions have produced great diversity in the distribution of marine organisms throughout known geologic time: temperature, depth of water, supply of food, degree of salinity, nature of the sea bottom, clearness of the water, etc.

**Significance of Fossils.** It would be difficult to overestimate the value of fossils in the study of earth history. They furnish most important evidence regarding earth chronology, ancient geographic and climatic conditions, as well as a basis for a proper understanding of the evolution, relations, and distribution of modern organisms.

"The materials with which the paleontologist must deal are the dead, unchangeable fossils, dug up from the rocks of the earth's crust, but the problems which arise from the study of these materials are far from dead, being filled with living interest and giving vitality to the whole field of historical geology. These now defunct fossils were once living, growing organisms, which were associated together in innumerable faunas, which lived in all portions of our earth, which followed one another in almost endless succession from the earliest recorded period of geological history to the present time, and which were adapted to all sorts of environmental conditions on the land and in the sea." (S. Weller).

1. *Earth chronology.* In any given region the best way to learn the relative ages of the stratified rocks is to determine their "order of superposition," the general assumption being that the older strata underlie the younger because the underlying sediments must have been first deposited. While this is a fundamental method, it is very limited in its application when used alone in regard to the construction of the whole earth's history. The succession of strata seen in any one locality or region represents only a small part of the earth's entire series and this, taken in connection with the fact that the lithologic character of strata of the same age frequently changes, makes it clear that "order of superposition" alone will not suffice to determine the relative ages of sedimentary rocks on a single continent or even large portion of a continent, not to

mention the utter inadequacy of the method when applied to comparing the relative ages of strata of different continents.

"Order of superposition," however, when used in connection with the fossil content of the strata, furnishes us with the method of determining earth chronology. "Life, since its introduction on the globe, has gone on advancing, diversifying, and continually rising to higher and higher planes. . . . Accepting, then, the undoubted fact of the universal change in the character of the organic beings which have successively lived upon the earth, it follows that rocks which have been formed in widely separated periods of time will contain markedly different fossils, while those which are laid down more or less contemporaneously will have similar fossils. This principle enables us to compare and correlate rocks from all the continents and, in a general way, to arrange the events of the earth's history in chronological order. . . . A geological chronology is constructed by carefully determining, first of all, the order of superposition of the stratified rocks, and next by learning the fossils characteristic of each group of strata." [1]

For the determination of geological chronology, certain organisms are more valuable than others, the best being those which have had wide geographic distribution and short geologic time range.

2. *Past physical geography conditions.* Typical stratified rock occupying any region proves the former presence of water over that region. By the study of the fossils we can further usually tell whether the water was ocean or lake, fresh or salt, open sea or arm of the sea, deep or shallow, close to or far from land, etc. Lithologic character alone may give some idea as to the depth of water and proximity to land where a given stratum was deposited, but the presence of considerable numbers of terrestrial organisms gives important additional data. Thick limestones filled with fossil corals point to long-continued conditions of clear sea water. Tree stumps, on the other hand, with roots still in their original position, plainly prove a former land surface. By means of fossils, many land areas have been proved to have existed as effective barriers to migrations of marine organisms.

3. *Past climatic conditions.* Some strata afford an idea of the climatic conditions under which they were laid down. Thus salt and gypsum beds, more or less associated with certain red sandstones or shales, indicate an arid climate at the time of their formation. But the study of fossils is much more fruitful in this connection. Certain strata in southern England contain fossil palms, gourds, crocodiles, etc.,

[1] W. B. Scott: *An Introduction to Geology*, 2nd edition, pp. 521-522, 525.

thus proving a subtropical climate for the time of their origin. Other strata, representing a later date in southern England, carry remains of Arctic animals and hence indicate a cold climate for that time.

Much strong evidence for climatic conditions over various portions of the earth during different geologic periods has been furnished by the study of true marine organisms. Certain kinds of corals live only in shallow tropical seas, and so, if in any region we find a bed of limestone rich in corals of this kind, it is to be inferred that this limestone was formed in warm, shallow sea water. Such coral limestones are known even in the interior of North America.

In deducing climatic inferences, as above explained, certain care must be exercised, because we are not justified in assuming that because a given species now lives under warm climatic conditions, every species of the same genus has lived under similar conditions. When, however, we are dealing with species still living, or in older rocks, with whole groups of organisms pointing to certain climatic conditions, we are reasonably safe in our inferences.

4. *Evolution of Life.* It is a well established fact that, as geological time went on, both plants and animals gradually evolved and, as a rule, became more and more complex in their organization. Single-celled plants lived in Archeozoic time. Even as far along in geological time as the early Paleozoic era there were no land plants and only invertebrate animals, mostly of low-order types. By middle Paleozoic time seedless land plants and low-order seed-bearing plants, including certain types of trees, appeared. About the same time low forms of vertebrates, such as primitive fishes had been evolved. In the later Paleozoic, amphibians evolved from fishes, and reptiles from the amphibians. During Mesozoic time reptiles dominated animal life, and birds and mammals evolved from the reptiles. Late in this era the true flowering plants, representing the most complex and beautiful forms of plants, made their first appearance. During the Cenozoic era plants and animals gradually became more and more modernized. Mammals dominated the animal world, and man evolved from the primate stock at about the beginning of the present (Quaternary) period.

5. *Relations and Distribution of Modern Organisms.* It is evident that, if we are to properly understand the present-day relations and distribution of organisms, we must learn about their ancestry and history, because all modern plants and animals have descended directly from those which lived in earlier geologic epochs. In many cases existing plants or animals, notably different in structure, can be traced back to a

common ancestry. Again, certain peculiarities in the distribution of some of the present-day animals are readily explained in the light of their geologic ancestry and habitats. A good example is Australia, where practically all of the present-day mammals (barring those introduced by man) are of very simple types, that is, non-placentals such as the kangaroo, spiny ant eater, etc., found only in and close to Australia, and which are clearly much more like the mammals of distinctly earlier geologic time than like typical mammals of the present day. The explanation is that Australia was separated from Eurasia before the higher (placental) mammals had been evolved, and that the very different, or probably much less severe, struggle for existence in isolated Australia has not been favorable for the evolution of placentals as was the case elsewhere.

## Rock Formations

**Nature and Naming of Formations.** By Stratigraphy is meant that branch of geologic science which "arranges the rocks of the earth's crust in the order of their appearance, and interprets the sequence of events of which they form the records" (A. Geikie). All stratified rocks may be subdivided into *formations* or groups of strata, each of which is marked either by a characteristic facies or assemblage of fossils, or, to greater or less extent, by similarity of lithologic (or rock) features, or by both. A rock formation is generally considered to be a mappable unit, that is its area can be delimited upon a geologic map. Subdivisions of formations are usually called members.

"The thickness of a formation or the length of time it may represent is not an essential feature. A single sequence might conceivably contain a formation thousands of feet thick and another only a few feet thick. The first might contain members each many times thicker than the entire second formation; or the second might be divided into several members and the first be undivided. . . . In naming formations it is the most general practice to adopt a geographic name derived from a "type locality" where the formation is present and sufficiently well exposed to constitute a standard of comparison. In practice it not infrequently happens that subsequent work reveals a better or more complete exposure than the type locality, and recourse is had to this as the actual standard rather than to the technical type locality. The geographic name selected is combined with either a lithologic term, if the formation is predominantly of one kind of rock, or the word "formation," if no single term is appropriate. This yields names like Dakota sandstone

Trenton limestone, Austin chalk, Genesee shale, Navarro formation, Dunkard formation, and Tejon formation" (J. B. Reeside).

**Distribution of Formations.** The distribution of a formation involves three considerations: (1) actual outcrops of the formation, (2) the existence of the formation where concealed under other rocks, and (3) where it was once present but has been removed by erosion. In the first case, in dealing with areas of outcrops of a bedrock formation, it often happens that either a small or large area comprises a single, bare exposure of the rock. More often, however, enough outcrops in an area project through a surface cover of loose, unconsolidated material, such as soil or alluvium, to make it practically certain that the whole bedrock of the area consists of a single formation. In the second case the problem is more difficult, but there are often ways of telling that a formation exists in small or large bodies concealed under other rocks as much as hundreds (or thousands) of feet below the surface. Thus an outcropping formation may be seen to extend into the earth under another formation; or the formation may be seen in one or more mining shafts; or its presence may be proved by examining the rock materials brought to the surface during the drilling of wells, many of which are thousands of feet deep.

In the third case the problem is still more difficult but, even so, surprising results may often be obtained. Thus in Figure 219 it is evident that part of the pile of strata (S), (say 1000 feet thick) formerly ex-

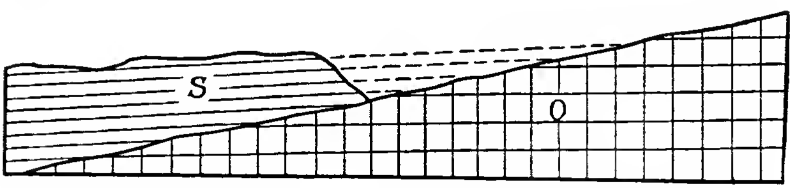



FIG. 219. Structure section to show how a pile of marine strata (S) formerly extended to the right over the old land (O) more or less as indicated by the broken lines.

tended to the right (say 10 miles) over the old land (O), more or less as indicated by the broken lines, but has been removed by erosion. Or scattering erosional remnants of a characteristic rock formation may prove that the formation once covered the whole area.

**Geological Maps, Sections, and Symbols.** A geological map shows the areal or surface distribution of rock formations or sets of formations. Such a map usually shows the areas of bedrock formations as they would appear at the surface, were there no superficial covering of loose, inco-

herent materials, such as soils, swamp deposits, etc. The superficial materials may be represented on a separate map, or by means of a special over-color or pattern on the bedrock map.

The distribution of each formation or set of formations is represented on the map by a certain color or pattern. At the border of the map there is a so-called legend which is an explanation of the colors or patterns employed. In the legend the various formations or sets of formations are arranged in regular order of age, with the oldest at the bottom. In many cases the surface distribution of formations, as shown on a geological map, gives no real indication of the actual extent of the formations in the crust of the earth. Thus extensive formations which have been notably tilted or folded may appear as only narrow belts at the surface (Fig. 220).

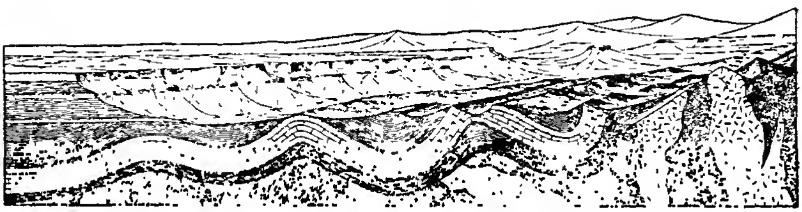


FIG. 220. Sketch map showing a structure section at the front, and a landscape beyond. (After U. S. Geological Survey.)

"In cliffs, canyons, shafts, and other natural and artificial cuttings the relations of the different beds to one another may be seen. Any cutting that exhibits those relations is called a section, and the same term is applied to a diagram representing the relations. The arrangement of the rocks in the earth is the earth's structure, and a section exhibiting this arrangement is called a structure section. Knowing the manner of formation of rocks, and having traced out the relations among the beds on the surface, the geologist can infer their relative positions after they pass beneath the surface, and he can draw sections representing the structure to a considerable depth. Such a section is illustrated in Figure 220. The kinds of rocks are indicated by appropriate patterns of lines, dots, and dashes. These patterns admit of much variation, but those shown in Figure 221 are used to represent the commoner kinds of rock." (U. S. Geological Survey.)

A columnar section contains a concise description of the formations which occur in a large or small area as they would appear if all piled up in one locality in order of age and in undisturbed condition. Such a

section involves a columnar diagram which shows the kinds and order of superposition of the formations, and data on either side of the diagram opposite each formation giving its thickness, description, age, and

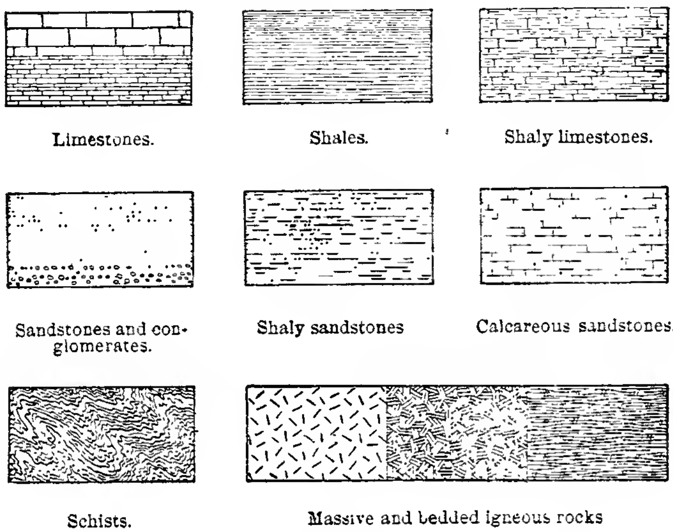



FIG. 221. Symbols used to represent common kinds of rocks. (After U. S. Geological Survey.)

usually its name (e.g. Fig. 252). Original structures, such as unconformities, are often shown, but subsequent structures, such as folds and faults, are seldom represented.

**Correlation of Formations.** By correlation of formations is meant the determination of the age equivalence, or practical equivalence, of rock groups or formations in various parts of the earth.

The student should bear in mind that strata cannot be determined as precisely contemporaneous, because geologic time has been very long and the evolution of organisms very slow, and almost exactly similar fossils may be expected in strata showing an age difference of at least some thousands of years. Also, at any given ancient time of earth history, as now, organisms were not the same in all parts of the world, so that rocks formed at exactly the same time in different parts of the world always show certain differences in fossil content. As compared with the vast length of geologic time, however, practical contemporaneity of the strata can usually be determined.

For the determination of geologic chronology, certain organisms are more valuable than others, the best being those which have had wide geographic distribution and short geologic range. For example marine organisms, which live near the ocean surface (so-called pelagic forms) and are easily distributed over wide areas, while, at the same time, the species are extant for only a comparatively short time, are the best

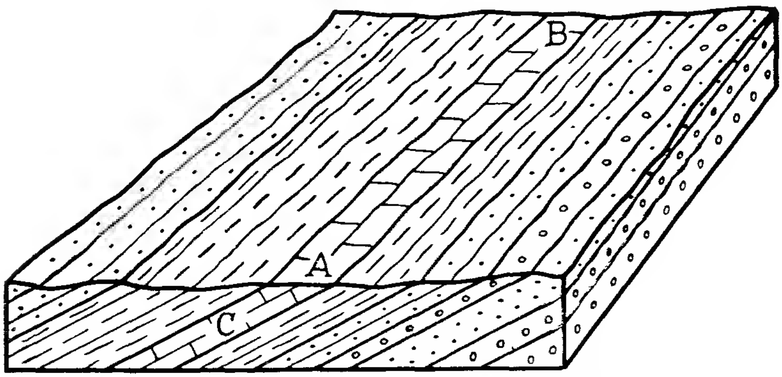



FIG. 222. A block diagram of part of the earth's crust with tilted strata. It illustrates correlation of formations by continuity of deposit from A to B as explained in the text. It also shows surface distribution of various formations and subsurface distribution in the structure sections at front and right sides.

chronologic indicators or *index fossils*. The graptolites of the early Paleozoic era furnish excellent illustrations.

In general the criteria of correlation may be divided into two classes, namely, geological (physical) and paleontological (biological).

I. GEOLOGICAL (PHYSICAL) CRITERIA. In many cases formations carry no fossils or very few, and it is then necessary to seek means of correlation without their aid. None of the geological (physical) methods can, however, be applied over wide areas such as opposite sides of a continent, or different continents. For such wide correlations, criteria derived from a study of fossils only can be used. Various physical factors used in correlation of formations are as follows:

1. *Continuity of deposit.* If, as shown in the accompanying diagram (Fig. 222), continuity can be traced from A to B, it is quite certain that the rock masses at A and B are of the same, or very nearly the same, age. There is probably no more important means of correlation used by the geologist except over wide areas.

2. *Similarity of materials.* Rock formations not actually continuous, though not too widely separated, are often correlated by noting similarity or identity of lithologic character, especially if there are any locally peculiar features. Earlier geologists were inclined to overwork this method of correlation by applying it over areas of too great extent, in some cases even suggesting identity of age of deposits on opposite sides of the ocean by this means. The danger of such application is apparent when we realize that, for example, a sandstone of very early (Cambrian) age may be exactly like sandstone of much later (Tertiary) age.

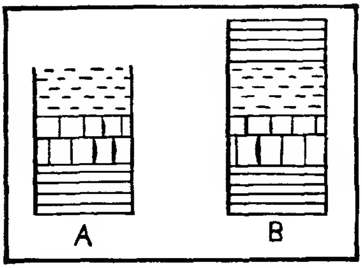



FIG. 223. Diagram to illustrate correlation of rock formations by similarity of sequence.

3. *Similarity of sequence.* A succession of strata in two places like A and B (Fig. 223), and not continuous on the surface, may be correlated on the basis of similarity of sequence, particularly when each formation at one place (A) shows little or no difference in lithologic character or thickness as compared with each formation at the other place (B).

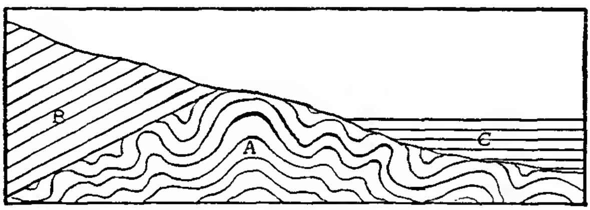



FIG. 224. Diagram to illustrate correlation of rock formations by degree of change or structure.

4. *Similarity of degree of change, or structural relations.* By finding similarly changed or metamorphosed rocks in the same vicinity, they may thus be correlated. For instance, in the accompanying diagram (Fig. 224) it is evident that the rocks of Group A are older than those of Group B, and these in turn older than C. Outcrops over limited areas at least can thus be placed in one of these three groups. This method cannot be used over wide areas such as different parts of a continent, because, for instance, certain strata (Cretaceous) in the east-

ern part of the United States may be unconsolidated and horizontal, while rocks of the same age are highly folded in the western United States.

5. *By diastrophism.* According to T. C. Chamberlin, the great deformations of the earth's crust have been of periodic occurrence. Each great movement has "tended toward the rejuvenation of the continents and toward the firmer establishment of the great (oceanic) basins." Between any two great diastrophic movements there has been a time of quiescence when the base-leveling processes have more or less lowered the continents. Such "base-leveling of the land means contemporaneous filling of the sea basins by transferred matter" with resultant encroachment of the sea over the land "essentially contemporaneous the world over," which in turn implies "a homologous series of deposits the world over." Thus the times of great diastrophism (recognized by great unconformities and overlapping deposits) should form the basis for separating and correlating at least the larger groups, or even systems, of strata in the earth's crust.

II. Paleontological (biological) criteria. We have already learned that "order of superposition" of the strata, studied in connection with their fossil content, furnishes the general standard for building up a geological chronology, and affords the best basis for the correlation of formations. In fact, for correlation of formations in distant portions of a continent, or different continents, paleontological criteria alone are satisfactory.

1. *Identity of species.* This is an extremely important method of correlation, especially when species with wide geographic distribution and short geologic range are employed. It is not wise to depend upon a single species for the correlation of far distant formations, because then the time necessary for the migration of the species must be considered. This seldom gives trouble because the geologist usually deals with a number of rapid-moving species. In a restricted area, where formations are to be correlated, the same organisms may have continued for a long time, but nearly always some peculiar species furnishes the clew.

2. *Aggregations of forms.* When groups of strata in different areas carry similar aggregations of similar forms, the groups of strata may be safely correlated. Even though a small percentage of the species vary, the method still holds because such variations are to be expected on account of migratory and geographic conditions.

3. *Stage in the evolution of organisms.* Since there has been a gradual development of life with increasing complexity throughout

geologic time, the stage of development or evolution shown by the fossils in a group of strata will serve as a basis for general correlation at least. Each era, or even period, shows a characteristic stage of evolution of forms.

4. *Percentage of living species.* This applies only to rock formations of later geologic time, because the older rocks contain no species like those now living. The percentage of living species becomes greater and greater as the present is approached, and on this basis Lyell subdivided a late period (Tertiary) into three epochs.

In any correlation problem the geologist strives to use as many of the above criteria as possible, the certainty of the correlation being more firmly established when several geological and paleontological criteria are used together.

## Significance of Unconformities

Thus far our discussion has been based largely upon the assumption of conformable strata, but many times the succession of strata (so-called "section") under study shows one or more unconformities. An unconformity represents an interruption in the stratigraphic succession. It is nearly always an erosional surface separating two sets of rocks. Rarely however, it may represent a time of almost complete non-deposition of strata in a submerged area.

In the case of an obvious unconformity, where the upper strata lie upon the eroded surface of tilted or folded strata, or of igneous or metamorphic rocks, the term "non-conformity" is applied (Fig. 244). If, however, two sets of strata, separated by an erosional surface, have their stratification practically parallel, the term "disconformity" is applied.

An unconformity signifies a gap or break in the geological record at a locality concerned, that is, an absence of both strata and the fossil record representing a greater or less length of geological time. The missing records for a given region can, however, generally be found by going to some other locality where deposition of sediments was not interrupted at the time when the unconformity was being produced.

Without the aid of fossils, in the ordinary case of unconformity, we could tell that the land emerged above water, was eroded, and again submerged, but we could not tell how much time was involved (Fig. 244). But by noting the fossils in the youngest strata just below the eroded surface, and in the oldest strata just above it, we could tell what epochs or periods the unconformity represents by a comparison with the

standard geologic divisions of the world (see table near the close of this chapter).

## Significance of Geosynclines

A relatively long, large subsiding downwarp or trough in which sediments accumulate to great depth during a long geological time is called a geosyncline. The sediments are generally of marine origin. In order of magnitude, geosynclines usually range from 100 to several hundred miles in width, and from several hundred to several thousand miles in length.

A typical geosyncline generally lasts through at least several geological periods, and sediments pile up in it to a depth of many thousands of feet—commonly 20,000 to 50,000 feet. Since the strata are of shallow-water origin as proved by coarseness of grain of much of the material, character of the fossils, ripple marks, mud cracks, etc., and since they pile up to such a great thickness, it is obvious that the floor upon which the sediments accumulate must subside more or less gradually during the process of deposition, and at about the rate of deposition.

The finest large-scale examples of geosynclines in the history of North America were the Cordilleran trough extending 3000 miles across the western part of the continent, and the Appalachian trough extending 2500 miles across the eastern part of the continent. Each of these lasted through most of Paleozoic time.

A remarkable fact is that, after long subsidence, a typical geosynclinal basin loaded with sediment is subjected to pressure at right angles to the axis of the trough, and folded and raised into a mountain range. This is because such a geosyncline marks a zone of exceptional weakness in the crust of the earth.

## Transgressions and Retrogressions of the Sea

During our study of the clearly recorded portion of the earth's history we shall find positive evidence of repeated transgressions and retrogressions of marine waters over various portions of what are now the continental areas. It is believed that such continental seas were comparatively shallow, that is, rarely as much as 1000 feet deep. Since subsidences or elevations of the lands are not the only known causes of sea transgressions and retrogressions, we shall, in the following pages, refer to submergences and emergences of the lands unless there is good evidence for more specific statement in any case.

Emergence or submergence of land may be caused either by (1) rise or sinking of the land; (2) rise or lowering of the sea; or (3) a combination of both.

The idea of periodic or rhythmic recurrence of diastrophic forces and events has become an important tenet of historical geology. It seems to have been a rule that times of activity—often very widespread—have alternated with times of quiescence. This is strikingly illustrated, as we shall learn, by the advances and retreats of marine waters over large parts of North America during the Paleozoic era. The most profound times of diastrophism, causing widespread emergence of land or great mountain-making, mark the close of the geologic eras, while lesser times of activity usually mark the close of the periods.

## Paleogeography

Paleogeography literally means "ancient geography" and deals with the geographic conditions of the earth during geologic time. In making a paleogeographic map to represent North America at a given time in its history, the attempt is made to show the relations of lands and waters, sometimes with distinctions between areas of marine and of continental deposition, location of highlands, etc. Until the present century there were only crude attempts at making such maps for North America, for the knowledge of the continent was not sufficient to form a reasonable basis upon which to work. Within the last thirty years, however, several sets of paleogeographic maps, notably those by Bailey Willis and Charles Schuchert, have been prepared. The maps used in this text are in the main based upon data (somewhat modified) from both the Willis and the Schuchert maps. The Schuchert maps are more numerous and detailed.

It should be borne in mind that such paleogeographic maps are generalized and rather tentative as regards many details—generalized because each map represents a considerable time period so that certain more local geographic changes during the period are not indicated, and tentative because of lack of knowledge concerning many areas and lack of certainty in the correlation of formations in certain other areas. With progress in knowledge of the strata, less generalized and more accurate maps will be made. Nevertheless the series of maps used in this text will serve to give the beginner a very good idea of the broader features in the geographic development of our continent.

## Classification of Geologic Time

We have already shown how, by employing the law of superposition of the strata together with the law of included fossils, the rock formations of various parts of the earth may be correlated and built up according to their natural order of age into a standard for comparison or a geologic column. The subdivisions of the geologic column represent the times when the successive rock formations were deposited. Different names have, from time to time, been assigned to these divisions, and these names are in more or less general use.

For a long time the subdivisions of the geologic column were made almost solely on the basis of marked differences in fossils, but it is now recognized that such differences were, in no small degree, caused by corresponding changes in the environment in which the organisms lived, or, in other words, by changes in the climate, the topography, the relations of land and sea, etc. So we now try to divide the geologic record at the points where the revolutionary physical changes are indicated, and to make corresponding divisions of geologic time itself. Thus there are two kinds of divisions—one for the rocks themselves, and the other for the time represented by the rocks.

The following time and rock scales have been adopted by the International Geological Congress. Immediately following these scales, there is presented the table of main geological divisions as now recognized in North America.

| *Time scale* | *Rock scale* |
|---|---|
| Era | Group |
| Period | System |
| Epoch | Series |
| Age | Stage |

The names of eras follow a definite plan depending upon the great life stages. Thus Archeozoic means literally "primitive or beginning life"; Proterozoic means "earlier or less primitive life"; Paleozoic means "ancient life"; Mesozoic means "intermediate life"; and Cenozoic means "recent life." The period names do not follow such a definite plan of nomenclature, various ideas being represented. These names will be explained when the different periods are taken up for discussion.

In the table below, the subdivision names of the Archeozoic and Proterozoic apply only to the Great Lakes region.

## MAIN DIVISIONS AND EVENTS OF GEOLOGICAL TIME

| ERAS | PERIODS | PHYSICAL EVENTS IN NORTH AMERICA | CHARACTERISTIC LIFE | | | YEARS AGO |
|---|---|---|---|---|---|---|
| CENOZOIC | Quaternary | Widespread rejuvenation and erosion | Age of mammals | Age of angiosperms | Rise of man<br>Modern plants and animals | 0<br>to<br>1,000,000 |
| | Tertiary | Great vulcanism in the west<br>Marine conditions over continental margins only | | | Rise of highest mammals except man<br>Great development of highest plants | 1,000,000<br>to<br>50,000,000 |
| MESOZOIC | Cretaceous | Rocky Mountain revolution<br>A great western-interior sea<br>Important chalk deposits | Age of reptiles | | Modernized angiosperms and [illegible] | 50,000,000<br>to<br>200,000,000 |
| | Jurassic | Sierra Nevada revolution<br>Widespread erosion<br>Some red beds in western-interior<br>Marine conditions on west coast | | Age of gymnosperms | First (reptilian) birds<br>First of highest forms of insects<br>First (primitive) angiosperms<br>Culmination of ammonites | |
| | Triassic | Widespread arid climate with great deposits of red beds<br>Marine conditions and much vulcanism on west coast | | | Earliest dinosaurs flying reptiles, marine reptiles, and primitive mammals<br>Cycads and conifers common<br>Modern corals common<br>Earliest ammonites | |
| PALEOZOIC | Permian | Appalachian revolution<br>Some red beds in western-interior<br>Great salt beds in western-interior<br>Extensive sea in the west | Age of amphibians | | Rise of primitive reptiles<br>Earliest cycads and conifers<br>Extinction of trilobites<br>Amphibians common and varied<br>First modern corals | 200,000,000<br>to<br>500,000,000 |
| | Pennsylvanian | Ouachita revolution<br>Warm, humid climate with a profusion of coal-making plants<br>Extensive sea in the west | | Age of spore plants | Earliest known insects<br>Culmination of amphibians<br>Spore plants abundant and varied | |
| | Mississippian | Ouachita disturbance<br>Two large marine transgressions | | | Rise of amphibians<br>Culmination of crinoids | |
| | Devonian | Acadian revolution<br>One great marine transgression | Age of fishes | | First known seed plants and forests<br>Great variety of boneless fishes<br>First evidence of ampbibians<br>Culmination of brachiopods | |
| | Silurian | Three great marine transgressions<br>Great limestone deposits<br>Great salt beds in the east | Age of invertebrates | Age of thallophytes | Earliest known land animals<br>Primitive land plants<br>Rise of fishes<br>Brachiopods, cephalopods, trilobites, crinoids, and corals | |
| | Ordovician | Taconic revolution<br>Three great marine transgressions<br>Very extensive limestone deposits | | | [illegible] | |
| | Cambrian | Green Mountains disturbance<br>Two great marine transgressions<br>Extensive deposits of clastic sediments | | | Trilobites and brachiopods common<br>Rise of pelecypods and cephalopods<br>Thallophytes | |
| PROTEROZOIC | Keweenawan | Extensive glaciation<br>Killarney revolution<br>Great vulcanism in the Lake Superior region | Rise of invertebrates | | Primitive water-dwelling plants and animals | 500,000,000<br>to<br>1,000,000,000 |
| | Huronian | Great iron-ore deposits<br>Earliest known glaciation<br>Great sedimentary deposits | | | | |
| ARCHEOZOIC | Timiskaming | Algoman revolution with great intrusions of granite<br>Extensive sedimentary deposits (all metamorphosed) | No animal fossils found | | Oldest known life (mostly indirect evidence) | 1,000,000,000<br>to<br>1,500,000,000 |
| | Keewatin | Laurentian revolution<br>Earliest known sedimentary and volcanic rocks (all metamorphosed) | | | | |

## LENGTH OF GEOLOGICAL TIME

How old are the Archeozoic rocks? If we attempt to answer this question in terms of years we encounter real difficulties, there being no definitely established exact standard for such measurement or comparison. In any case the time is utterly inconceivable to us, the important thing to bear in mind being that the great events of well-known earth-history which have transpired since the formation of the oldest known Archeozoic rocks have required a lapse of at least scores of millions of years. Among such events have been the long, slow, generally progressive evolution of life; the enormous accumulations of sediments at many times and places; the repeated advances and retreats of the sea over many parts of the continents; the building up and wearing away of mountain ranges at many times and places; as well as various other profound changes which have affected the face of the earth. On the basis of such geological happenings, an exceedingly conservative minimum estimate of the age of the Archeozoic rocks is 100,000,000 years.

Measurements of time on the basis of radioactivity run much higher. In radioactivity a chemical element of higher atomic weight is transformed into one of lower weight. Thus uranium changes through successive stages of radium into a certain type of lead. The rate of this change is said to be rather accurately known, so that the determination of the amount of the special type of lead in minerals containing uranium affords a means of ascertaining at least approximately the time when the transformation started. Based upon this principle, an age of considerably more than a billion years has been assigned to the Archeozoic rocks; the Paleozoic era opened more than 500,000,000 years ago; the Mesozoic era nearly 200,000,000 years ago; and the Cenozoic era at least 50,000,000 years ago.

# CHAPTER XVI

## ORIGIN AND PRE-GEOLOGIC HISTORY OF THE EARTH

If we define geology as the study of the history of the earth and its inhabitants as revealed in the rocks, it is evident that the problems of the origin and very early development of the earth are strictly astronomic rather than geologic. It is generally agreed that geologic history did not begin till the ordinary earth processes, such as weathering and erosion, transportation and deposition of sediments, etc., began to operate. Since, however, the pre-geologic condition of the earth must have gradually given way to its geologic condition, it is a matter of interest for the geologist to consider the hypotheses regarding the very early development of the earth.

### The Solar System

The sun has a diameter of about 866,000 miles, and a volume 1,300,000 times that of the earth. Around this central sun nine planets—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto—revolve in nearly circular orbits. Three of these planets—Mercury, Venus and Mars—are smaller than the earth, while the others are larger, Jupiter being 1,300 times as large. The earth is about 93,000,000 miles from the sun and requires one year for a trip in its orbit around the sun, while Neptune, a very distant planet, is about 2,800,000,000 miles from the sun and requires 164 years for a revolution about the sun. Each planet also rotates upon its axis, the earth accomplishing a rotation every twenty-four hours. Most of the planets have smaller bodies called satellites or moons revolving about them, such as Earth with its one moon, Saturn with eight moons, etc. The sun and the nine planets with their satellites, together with a group of many small independently revolving bodies called "planetoids," comprise the solar system. That this solar system constitutes only a very small part of the universe is clearly proved by the fact that the nearest fixed star is several trillions of miles from the earth.

Some of the well-known facts which any hypothesis of the origin of the solar system must explain are as follows: (1) The planet orbits are all elliptical, but nearly circular; (2) the orbits lie in nearly the same

plane; (3) all planets revolve about the sun in the same direction; (4) the sun's direction of rotation is the same as that of the planets' revolution; (5) the planes of the planets' rotation nearly coincide with the planes of their orbits (except Uranus and Neptune); (6) the direction of the planets' rotation is the same as that of their revolution; and (7) the satellites revolve in the direction of rotation of their planets (two or three exceptions).

## Hypotheses of Earth Origin

**Nebular or Ring Hypothesis.** In 1796 Laplace published a remarkable work on astronomy, and in it, incidentally, he put forth his now well-known hypothesis regarding the origin of the solar system. He postulated a spheroidal mass of very highly heated, incandescent gas or nebula greater in diameter than the present solar system, this whole mass rotating in the direction of the revolution of the existing planets. Due to loss of heat by radiation, this mass contracted and its shrinkage necessarily made it rotate more rapidly upon its axis, at the same time causing the centrifugal force on its outside to become stronger and stronger. Finally the centrifugal force at the equator became equal to the force of gravity and the equatorial portion was left off (not thrown off) as a ring surrounding the contracting remainder. The materials of the ring condensed to form the outermost planet. By continued contraction of the rotating nebula, the other rings and planets were formed. The satellites were produced in a similar manner by rings left off by the shrinking planets.

Briefly, according to this hypothesis, the earth was originally highly heated and much larger than now. During its cooling and contraction, its original hot and dense atmosphere, which contained all the earth's water in the form of vapor, gradually became thinner due to absorption by the earth. When the conditions of pressure and temperature were favorable, water vapor condensed to form the hydrosphere. The oldest rocks must have been igneous, that is, they were portions of the original crust formed by cooling of the molten globe.

For over a hundred years the Laplacian hypothesis exerted a profound influence upon science, philosophy, and theology, and certainly many of the important phenomena of the solar system are explained by it. Some serious objections to it may, however, be briefly stated as follows: (1) Nearly all existing nebulas are spiral and not circular; (2) spectroscopic study shows that these nebulas do not consist of gas, but rather of discrete liquid or solid particles; (3) the backward revolutions of certain

satellites oppose the hypothesis; (4) rings could not have been left off, that is, there could have been no intermittent process of the sort; and (5) it is not at all clear how the matter of the rings could have condensed into planets.

**Planetesimal or Spiral Hypothesis.** It is a remarkable fact that, although many thousands of nebulas are known, there are very few examples of ring nebulas of the Laplacian type among them. Spiral forms are very common, especially the smaller ones. Also, as above stated, spectroscopic study of these nebulas shows them to be made up of discrete (liquid or solid) particles rather than of gas. The Planetesimal hypothesis, formulated by Chamberlin and Moulton, "postulates that the matter of which the sun and the planets are composed was, at a previous stage of its evolution, in the form of a great spiral swarm of discrete particles whose positions and motions were dependent upon their mutual gravitation and their velocities" (Moulton). A nebula of this sort comprised a luminous central mass (the future sun) from the opposite sides of which two luminous spiral arms streamed out with occasional larger masses or knots along each arm, and with dark lanes between the arms (see Fig. 225). Also some nebulous matter occupied the spaces between the arms. Such a distribution of matter in a spiral shows that the form could not have been maintained by gaseous pressure, as in the Laplacian hypothesis, but rather by the movements of the separate particles or masses. Since these particles are thought to have moved like miniature planets, they are called planetesimals. Each planetesimal is considered to have moved in its own orbit around the central mass. The planetesimals did not move along the arms of the spiral, but rather crossed them at considerable angles (Fig. 226). "When we see a spiral we do not see the paths which the separate masses have described, but the positions which they occupy at the time. In the present case (Fig. 226) if a smooth curve is drawn through the regions where the matter is densest, it will

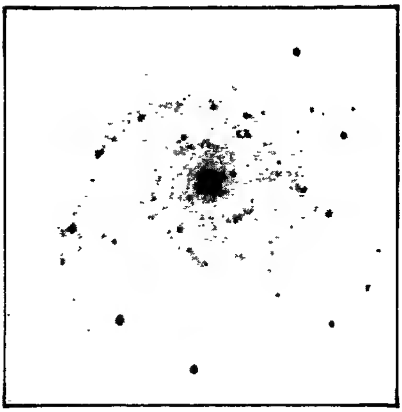


FIG. 225. A very symmetrical spiral nebulation in Pisces (M. 74). Photo by Lick Observatory. (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company.)

form a sort of double spiral as represented by the full lines" (Moulton). The dotted lines in the figure represent orbits of some of the particles or knots.

The planetary bodies, including the earth, began as hot gas-bolts shot out from the sun, and, in cooling, each of these gas-bolts condensed to a nuclear body or knot associated with myriads of planetesimals. Largely because of the crossing of orbits, the knots or nuclei increased in size by a gathering in or accretion of planetesimals. Meteorites, which now

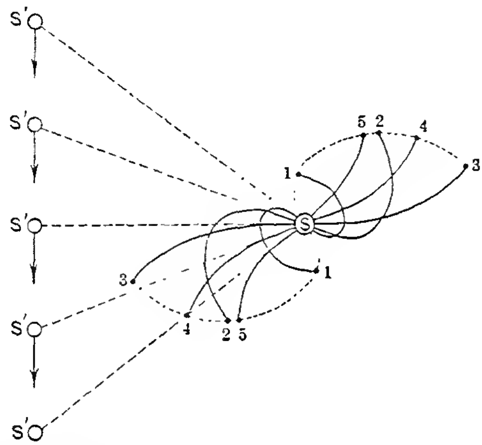



FIG. 226. Diagram to illustrate the formation of a spiral nebula. S, sun; S′, passing star whose direction of passage is shown by the arrows. The curved lines show the paths followed by nuclear (planetary) masses (numbered dots) pulled out from S by S′. The straight lines are the paths which the planetary masses would have followed had S′ remained stationary in each of the positions indicated. The curved dotted lines pass through zones containing planetary and other nuclear masses, thus producing the two luminous spiral arms of the nebula. (Modified after Moulton.)

strike the earth, are thought to be planetesimals still gathering in, though at a very slow rate.

The origin of the spiral is believed to have been caused partly by strong tidal disrupting effects generated in the central body (sun) by a passing star, and partly by eruptive activity of the sun itself. The separated masses at first moved straight toward the passing star, but, because of change in position of the passing body, they gradually became pulled around and their paths curved into spirals as shown by Figure 226. In accordance with the principle of the well-known tide producing force, similar masses must also have shot out from the opposite side of the sun or central body. Finally, when the passing star had so far gone by as to

have largely lost its power of very effectively attracting the sun, the spiral orbits of the planetesimals and larger planetary bodies gradually became coiled into elliptical, nearly circular orbits around the sun which then became the central attracting body.

Briefly, according to this hypothesis, the earth was never, except in its very early nuclear stage, a highly heated gas and never necessarily more highly heated than at present, hence sedimentary as well as igneous materials may well be expected among the earliest formed rocks. Instead of a much larger original earth, it increased in size by accretion of planetesimals. With increase in size came increase in force of gravity, causing compression of the earth's matter and generation of more and more interior heat (probably aided by radioactivity), thus inaugurating volcanic activity. Accompanying this increasing pressure and heat, gases (including water vapor) were driven out to form an atmosphere which gradually became larger and denser. When the water vapor had sufficiently accumulated, precipitation resulted to initiate the hydrosphere.

**Modification of the Planetesimal Hypothesis.** Jeans and Jeffreys have set forth what may be termed a modification of the planetesimal hypothesis, very briefly summarized as follows. The disruption of the sun by a passing star was caused by the tide producing force with little or no aid from the eruptive activity of the sun. Instead of hot gas-bolts shot out from the sun from time to time, a long streamer of very hot gas was steadily pulled out of the sun by the passing star and drawn forward by the star. This streamer, which reached to the outer boundary of the solar system, became disrupted into ten parts which formed into spheres—nine of them planets, and one of them the group of the planetoids. When the passing star moved far enough away the planetary bodies, then dominated by the attractive influence of the sun, began to revolve around the sun in orbits.

According to this hypothesis the earth was originally a highly heated, incandescent gas. Then it cooled to full-size molten condition. About the beginning of geological time a solid crust formed over the fluid interior. The earth was then surrounded by a very thick, hot, dense atmosphere which in time cooled enough so that its contained water vapor could condense in tremendous quantities and thus produce the oceans. As cooling and solidification proceeded, lighter rocks were formed in the outer shell of the earth, and heavier and heavier material downward toward the center.

**Was the Earth once Molten?** Certain facts about the present-day earth rather strongly indicate that it was once in a molten condition.

Thus the specific gravity of the earth as a whole is much higher than that of its outer shell. In a molten earth the heavier materials would naturally gravitate toward the center. Also studies of the passage of earthquake waves in the earth, particularly their velocities, strongly indicate the existence of several earth-shells—an outer shell of lighter (granitic) rocks about 37 miles thick; a deeper shell of distinctly heavier (basaltic) material about 1800 miles thick; and a central still heavier liquid or metallic core over 4000 miles in diameter. Earthquake waves of transverse vibrations do not pass through the great central core. Such waves, as far as definitely known, pass through solids only, and hence the inner part of the earth is probably still molten.

Certain other facts seem opposed to a once molten globe. Thus climatic changes and conditions necessary for living things were, in earlier geological time, essentially like those of today, so how could there have been a very hot, dense, enormous atmosphere which has gradually diminished in all these respects? Also "a globe, whose mobile liquid material has been arranged in accordance with its density . . . . possesses little potential opportunity for deformation, except for shrinkage due to cooling. . . . Cooling from the earliest solidification to the present earth temperatures would not cause enough contraction to account for the wrinkling which the earth shell shows today." (R. T. Chamberlin.)

# CHAPTER XVII

## THE ARCHEOZOIC ERA

### The Oldest Known Geological Records

In earth history, as in human history, the recorded events of earliest times are fewest and most obscure, and hence the least intelligible of all. In spite of a certain disadvantage in beginning with the least known part of the history of the earth, the only satisfactory method of presenting the subject is "to follow the natural order of events. This has the great advantage of bringing out the philosophy of the history—the law of evolution" (J. Le Conte). The earliest known geological history is recorded in the rocks of the Archeozoic group, often called the Archean. While it is true that the most obscure records of any rock group are here, partly because the original structures of these rocks have generally been so profoundly changed (metamorphosed) and partly because of the almost complete absence of well-defined fossil forms, nevertheless, certain very definite and important conclusions regarding the earliest known era of geologic time may be reached through a study of the Archezoic rocks which are believed to be more than one billion years old.

### General Nature and Origin of the Archeozoic Rocks

"Archean Complex," "Basal Complex," "Fundamental Complex," etc., are all terms which have been applied to the rocks of the Archeozoic group which invariably occupy a basal position with reference to all other rock groups. The Archeozoic group is a crystalline complex, comprising various kinds of igneous rocks and metamorphosed strata, beneath the base of the more or less well-determined sedimentary succession.

Briefly stated, the Archeozoic group exhibits the following characteristics: (1) So far as observed, it always shows a profound unconformity or erosion surface at its summit; (2) its lower limit or base has never been determined, and is likely inaccessible; (3) its thickness is very great, at least tens of thousands of feet, and possibly many miles; (4) its rocks are always crystalline and usually highly metamorphosed and

tilted or folded; (5) it comprises a most heterogeneous group of rocks, often intimately associated, such as lavas and tuffs; schists, quartzites, and marbles, representing shales, sandstones, and limestones which have been highly metamorphosed; some beds of iron ore; and great volumes of plutonic rocks, especially granites and granitic gneisses; (6) the igneous rocks almost always greatly predominate; (7) it rarely, if ever, contains distinct fossils, though certain evidences of life do exist; and (8) as far as known it is universally present at or under the earth's surface.

### Distribution of Archeozoic Rocks

As far as known, Archeozoic rocks appear to be universally present at or below the earth's surface. If this be true, and all evidence strongly favors such a view, it is a most remarkable characteristic of the Archeozoic, because no other rock group has such a distribution. There is a widespread surface distribution of Archeozoic rocks, in large and small areas, throughout the lands of the earth.

On the accompanying map (Fig. 227) the surface distribution (areas of outcrops) of pre-Cambrian (Archeozoic and Proterozoic) rocks in North America is shown. Most of these areas contain more or less Archeozoic. The map shows the greatest area of pre-Cambrian rocks in North America to be around Hudson Bay. This vast area of fully 2,000,000 square miles contains much Archeozoic. Among the principal smaller areas containing Archeozoic rocks are those of Newfoundland, New England states, Adirondack Mountains, Piedmont Plateau, Michigan, Wisconsin, Minnesota, and numerous areas in Alaska, and in the Rocky Mountain district and westward. In drilling deep wells in many places, particularly in the upper Mississippi Valley, rocks of the pre-Cambrian complex have been encountered, and so we may be confident of the presence of Archeozoic under cover of thousands of square miles of later rocks. These facts of distribution, together with the fact that wherever erosion has gone deep enough the Archeozoic never fails, leave little room for doubt concerning the universal presence of these rocks in North America.

### Subdivisions of the Archeozoic Group

In most regions where it has been studied, the Archeozoic group consists of two or more distinctly different classes of rocks—metamorphosed strata of various kinds, plutonic rocks of different kinds (mostly granite), and often metamorphosed volcanic rocks. In many places these

rocks may be separately mapped as such, but in many others different kinds are so intimately mixed or associated as to preclude separate mapping. In every known region the very oldest are surficial rocks of either sedimentary or sedimentary and volcanic origin, and these are cut or

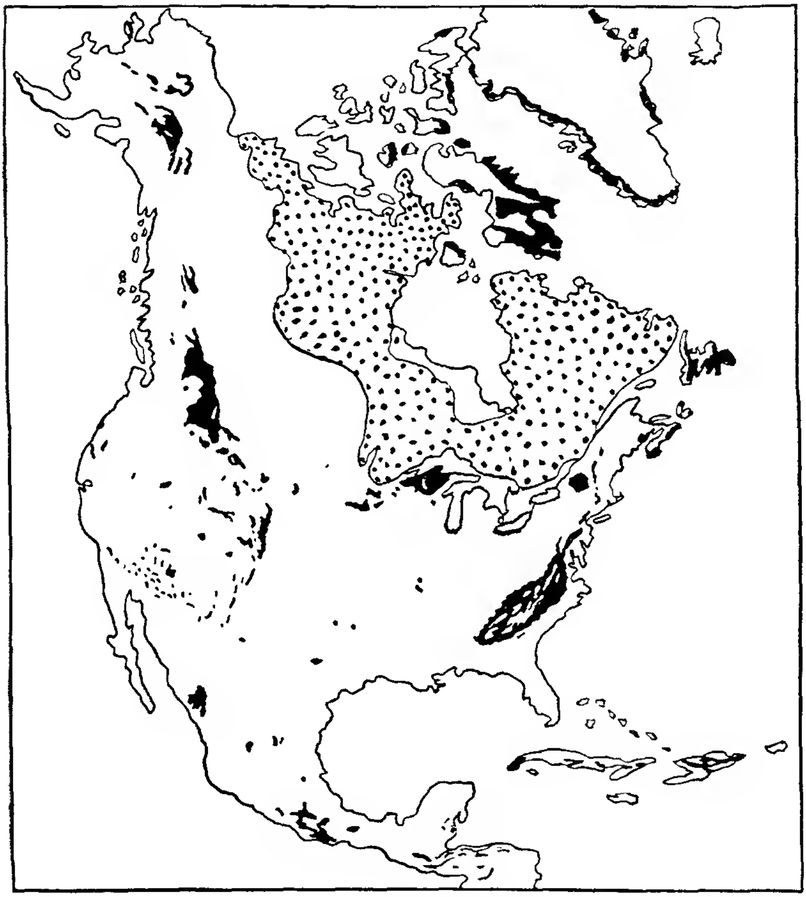


FIG. 227. Map showing the surface distribution of pre-Cambrian (Archeozoic and Proterozoic) rocks in North America. Largest area shown by dotted pattern; smaller areas by solid black. (Modified after Willis, U. S. Geological Survey.)

intruded by (younger) plutonic rocks. The present state of our knowledge does not warrant the subdivision of the Archeozoic anywhere into more than two definite periods or systems. In most regions not even two such subdivisions have been determined.

The following tabular summary shows the subdivisions of the Archeozoic and their relation to the younger Proterozoic in a portion of North America where a fine display of widely exposed older pre-Cambrian rocks have been carefully studied. This may be regarded as the type Archeozoic region of the continent.

| | *Lake Superior–Lake Huron Region* |
|---|---|
| Proterozoic | Huronian system |
| | (Great unconformity) |
| Archeozoic | Algoman granite. (Extensive batholithic intrusive bodies.)<br>Timiskaming system, including Sudbury, Knife Lake, Seine River, Doré, and other series. (Sedimentary rocks, locally with volcanics, highly metamorphosed.)<br>(Unconformity, small to great)<br>Laurentian granite.<br>Keewatin system, including the Coutchiching series. (Largely volcanic rocks, with more or less associated sedimentary material. All rocks highly metamorphosed.) |

## Lake Superior–Lake Huron Region

**Keewatin System.** The *Keewatin* system of rocks has a widespread distribution, outcropping in many large and small areas across southern Ontario in Canada, and in northern Minnesota and northern Michigan in the United States. It includes the oldest determined rocks in the region, and no rocks anywhere else are known to be older.

The Keewatin is a highly metamorphosed complex of lava-flows and tuffs with some intercalated beds of original sediments now in the form of slates, schists, and certain iron-rich rocks. They are usually gray or dark green. Even the volcanic rocks have often been rendered schistose by metamorphism. In spite of the fact that the rocks are generally much metamorphosed, enough diagnostic features are preserved to prove their origin.

In most places the Keewatin rocks show steep dips because they have been strongly folded. They are commonly thousands of feet thick —in some places more than 20,000 feet. The full thickness is not known, first, because the upper part of the original pile has been profoundly affected by erosion, and, second, because the bottom of the pile has never been found. The fact that they are surficial rocks makes it certain that they must have accumulated on top of still older rocks. It would indeed be interesting to know the nature of those still more ancient rocks. Future researches may tell us, that is if such very ancient

pre-Keewatin rocks still exist. If so, a still earlier chapter will be added to our knowledge of earth history.

**Laurentian Revolution and Granite Intrusion.** After the accumulation of the great Keewatin system of rocks, the so-called *Laurentian* granite was intruded into it in the form of batholiths throughout much of the region. The Laurentian granite is the oldest known plutonic rock. The heat and pressure of the rising magma helped to metamorphose the Keewatin rocks.

The granite intrusions accompanied a widespread though rather moderate degree of folding of the Keewatin rocks. This folding, accompanied by the intrusions and uplift, may be called the *Laurentian Revolution.* This is the earliest definitely known deformation of the earth's crust.

After (and in part during) the Laurentian Revolution, and before the next oldest (Timiskaming) rocks were formed, the whole Keewatin region was more or less deeply eroded. This we know, first, because the folds were truncated by erosion, and granite batholiths were laid bare, before the Timiskaming rocks were laid down upon them, and, second, because pebbles and boulders of both Laurentian granite and Keewatin rocks are common at the bottom of the Timiskaming system.

**Timiskaming System.** A great system of rocks, very largely sedimentary in origin, directly overlies the Keewatin system in many places from western Quebec westward across Ontario and also west and south

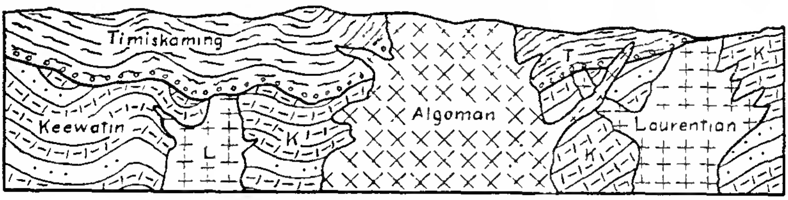



FIG. 228. A highly generalized section, about 25 miles long, showing the relations of the Archeozoic group of rocks in the Lake Superior-Lake Huron region of Canada. The Keewatin system was moderately folded and intruded by the Laurentian granite, after which there was deep erosion. Then the Timiskaming rocks were laid down, and later strongly folded and intruded by the Algoman granite, after which there was another period of profound erosion, marked by the upper surface.

of Lake Superior. Where the rocks of this age are particularly well exposed in a large region in western Quebec and eastern Ontario, they have been named the *Timiskaming* system. Rock series such as the Sudbury, Seine River, Doré, Knife Lake, and others, which have been inde-

pendently described and named in various parts of the larger region, are now rather confidently believed to represent parts or series of one great system—the Timiskaming—which is widespread throughout the Lake Superior-Lake Huron region.

The basal portion of the Timiskaming system is nearly always a great conglomerate formation. The upper portions consist largely of quartzites, slates, schists, graywackes, and so-called iron formation, often with interbedded lavas and tuffs. Crystalline limestone seldom occurs. Nearly all of the now altered sediments seem to be of non-marine or continental origin. The whole system in places, such as the Lake Timiskaming and Sudbury regions of Ontario, reaches a thickness of 20,000 feet or more. Thicknesses of thousands of feet are common.

There has been some difference of opinion as to whether the Timiskaming should be regarded as Archeozoic or Proterozoic. Several careful students of the subject have pointed out that the Timiskaming and Keewatin are distinctly more closely related than the Timiskaming and the next overlying (Lower Huronian) rocks of Proterozoic age. Thus the erosional surface (unconformity) separating the Timiskaming and Keewatin, and also the structural differences and degree of metamorphism of the two systems, are much less pronounced than those between the Timiskaming and Lower Huronian. For these reasons it seems best to classify the Timiskaming with the Archeozoic.

**Algoman Revolution and Granite Intrusion.** After the great Timiskaming system of sediments and associated volcanics was laid down, the Lake Superior-Lake Huron region experienced a second period of strong diastrophism—this time much more intense than that of the first (Laurentian) disturbance. It has been called the *Algoman Revolution.* Accompanying the orogenic movements, great and widespread batholiths of plutonic rocks, commonly called *Algoman* granite, broke into, cut to pieces, and helped to disturb and metamorphose both the Keewatin and Timiskaming systems.

Not only in the Canadian region, but wherever the Proterozoic rocks of North America have been found resting upon the Archeozoic, the two sets of rocks are separated by a profound unconformity representing a very long interval of erosion. Evidently North America stood well above the sea for a long time, and was nearly leveled by erosion, before the oldest known Proterozic strata were laid down.

### Archeozoic of Southeastern Canada and Northern New York

Throughout southeastern Ontario, southern Quebec, and the Adirondack Mountains of northern New York, the oldest known pre-Cambrian rocks are highly metamorphosed sediments constituting the great *Grenville* system. It is many thousands of feet thick. It consists largely of schists, quartzites, and crystalline limestones representing highly metamorphosed shales, sandstones, and limestones. Some altered igneous rocks seem to be contemporaneous with the strata. The Grenville strata

Fig. 229. Archeozoic (Grenville) metamorphosed strata in the central Adirondacks. Note the distinct stratification in these highly crystallized rocks.

have been so profoundly changed from their original condition that certain of the highly sedimentary features have been completely obliterated. Thus the absence of water-worn particles and fossil forms, both of which are so characteristic of ordinary strata, is due to complete crystallization (metamorphism) of the Grenville strata since their deposition. There are, however, certain proofs of the sedimentary origin of the Grenville. The fact that these rocks commonly occur in alternating layers, including extensive beds of crystalline limestone and quartzite, furnishes strong evidence that this distinct banded effect is due to differences in original sedimentation (Fig. 229). In some places the strata are so filled with graphite flakes that the mineral is mined. Carbon ex-

isting under such conditions is doubtless of organic origin and represents (in crystallized form) the final stage in the decomposition of organisms which lived in the waters while the Grenville strata were being deposited.

In the western part of southeastern Ontario the Grenville contains some altered lava-flows, and it is there overlain unconformably by the *Hastings* system of metasediments at the base of which there is a conglomerate formation.

After the deposition of the Grenville-Hasting strata, igneous activity took place on a grand scale throughout southeastern Canada and northern New York. Tremendous bodies of molten rock, varying in composition from gabbro to granite, were forced into the strata from below. The present distribution and mode of occurrence of these igneous rocks shows that the molten masses broke into the Grenville strata in a very irregular manner.

After the disturbance of the Grenville system, and the intrusion of the great batholiths into it, the whole area of southeastern Canada and northern New York was subjected to very profound erosion.

The Grenville has never been definitely correlated with any rock system or series farther west in Ontario. The fact that it is universally so highly metamorphosed points strongly to its great antiquity. Except for the fact that the Grenville (metasediments) and Keewatin (largely metavolcanics) are different in origin, the Grenville-Hastings-batholith succession suggests correlation with the Keewatin-Timiskaming-batholith succession farther west.

## Archeozoic Rocks Elsewhere in North America

In the vast region of pre-Cambrian rocks surrounding Hudson Bay (Fig. 227), there are many occurrences of Archeozoic rocks more or less similar to those already described.

Rocks quite certainly of Archeozoic age occur in various places in the Piedmont Plateau of the eastern United States. For example the *Baltimore* gneiss of Maryland is a very ancient sedimentary formation, highly metamorphosed and rather thoroughly injected with granite. The *Fordham* gneiss of New York City and vicinity is similar. Both of these gneisses lie unconformably below great series of metamorphosed strata which are regarded as of Algonkian (Proterozoic) age and which unconformably underlie early Paleozoic strata.

In the Rocky Mountains there are Archeozoic rocks, mainly granites,

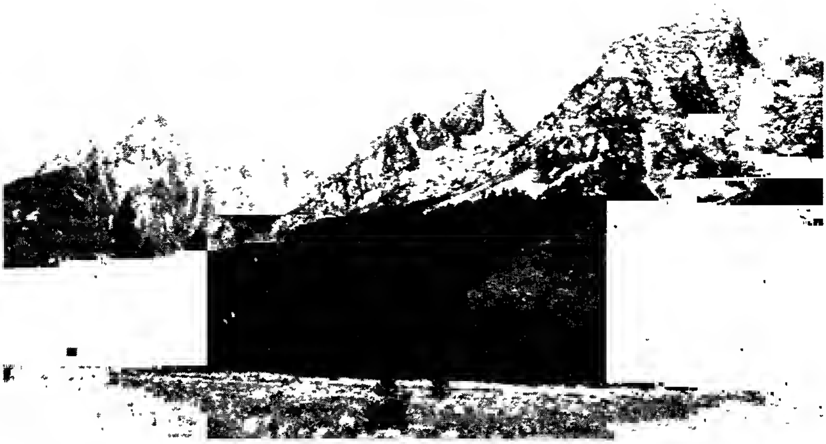


FIG. 230. Mountains of Archeozoic granite rising to heights of 13,000 feet or more above sea level. Teton Range in Grand Teton National Park, Wyoming.

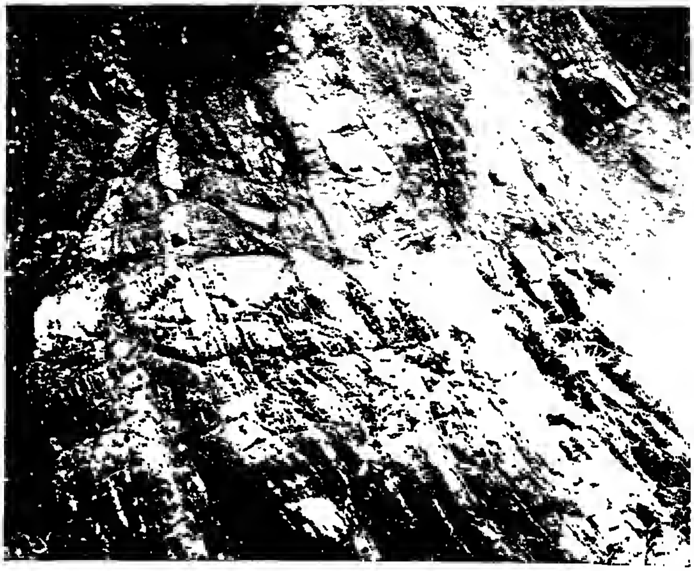


FIG. 231. A detail view of steep-dipping Archeozoic schist intimately injected, parallel to its foliation, with granite, forming a mixed gneiss. Width of outcrop about 12 feet. Western San Gabriel Mountains, California.

often intimately associated with still older schists in many places. Thus they form the outcropping cores or axes of the Laramie, Wind River, Big Horn, Grand Teton (Fig. 230), Sangre de Cristo, and Colorado Front Ranges.

In the depths of the Grand Canyon of Arizona, Archeozoic rocks are exposed for many miles. They comprise the *Vishnu* system of predominantly highly metamorphosed strata—schists, quartzites, etc.—at least 25,000 feet thick, cut by numerous large and small granite dikes. A very profound unconformity separates these rocks from overlying Algonkian (Proterozoic) strata.

In various parts of southern Arizona and southern California, Archeozoic metasediments, schists, gneisses, and granites and other plutonics are well exposed (Fig. 231).

## Life and Climate of the Archeozoic Era

If the term "Archeozoic" is properly applied, rocks of that age should show the earliest evidences of life. Beds of graphite-rich schists; numerous scattering flakes of graphite in certain Archeozoic crystalline limestones and quartzites; extensive beds of limestone; and beds of iron ore which were derived from carbonates, altogether quite certainly imply the existence of life in Archeozoic time. Limestone has sometimes been of chemical origin, but the presence of clearly bedded graphitic schists and crystalline limestones in a distinctly sedimentary system of rocks almost certainly shows the influence of organisms in the production of both the graphite and the limestone. "Since we know that algae alone are capable of chemically precipitating lime carbonate, the presence of enormous quantities of (Archeozoic) limestone in this region (southeastern Canada), now mainly altered to marble, strengthens the evidence in favor of life in the Archeozoic."

Fossil forms of low-order single-celled plants (algae) have been reported from Archeozoic rocks in Minnesota.

Certain hemispherical masses (called "Eozoön"), made up of indistinct, crudely concentric layers of carbonate of lime, were found many years ago in the Grenville limestone. They were probably secreted from water by primitive algae as were similar, better preserved masses occurring in Proterozoic limestones (Fig. 236).

The later Archeozoic (Seine River) crystalline limestone in the Rainy Lake region of southwestern Ontario has yielded crude, cone-shaped masses (called "Atikokania") several inches or more in diameter.

They have both concentric and radial structures. Their origin is not positively known, but they probably represent single-celled plant secretions.

With the exceptions above mentioned, almost nothing like determinable fossil forms have been found in Archeozoic rocks, and even if such ever were present they must have been almost entirely obliterated by the intense metamorphism to which the rocks have been subjected. In the light of the evolution which took place during much better known geologic time, it is quite certain that the Archeozoic organisms must have been much simpler forms than those of the early Paleozoic which, in turn, were much simpler than those of the present day.

All we can say about Archeozoic climate is that, during most or all of the time, it was favorable for the existence of life and for ordinary geologic processes such as erosion and sedimentation.

# CHAPTER XVIII

## THE PROTEROZOIC ERA

THE Proterozoic era, represented by the Proterozoic group of rocks, includes the time between the Archeozoic and the earliest Paleozoic (Cambrian) period, the Cambrian system comprising the oldest known rock system with abundant fossils. The term "Algonkian" was at first, and still often is, applied to the group of rocks now more generally and satisfactorily called Proterozoic.

### GREAT UNCONFORMITY BETWEEN THE ARCHEOZOIC AND PROTEROZOIC GROUPS

As already stated, whenever observations have been made under favorable conditions, the summit of the Archean complex appears to be marked by a profound unconformity. Such an unconformity, however, cannot be universal because the very fact of extensive erosion of certain areas implies the deposition of the eroded sediments in other areas. Such sediments, if found, would contain the records of the time interval indicated by the great unconformity. So far at least, this sedimentary record has not been brought to light, probably either because (1) these sediments were deposited in ocean basins not since exposed as dry land; or (2) these sediments are not at present exposed to view because concealed under later formations; or (3) these sediments have not been recognized as such. Also it is not at all unlikely that some or even many of these sedimentary areas may subsequently have become land areas so that, as a result of erosion, more or less of the sediments were there removed again to be deposited as Proterozoic or later sediments. Future researches may bring to light some of the now "lost records" which represent the great unconformity or time gap between the Archeozoic and Proterozoic.

### GENERAL NATURE AND ORIGIN OF THE PROTEROZOIC ROCKS

The Proterozoic group includes all the stratified rocks and their metamorphosed equivalents, together with associated igneous rocks, which occupy a stratigraphic position between the earliest Paleozoic (Cambrian) and the Archeozoic. Stratified rocks greatly predominate

over igneous rocks, and some fossil remains of both plants and animals occur in them.

An important feature, especially of the later Proterozoic rocks, is the frequent presence of great series of non-metamorphosed strata which are therefore the oldest known unaltered strata of the geologic column. Such strata include all common types of sedimentary rocks as conglomerates, sandstones, shales, and limestones. Basal conglomerates, which were derived from the lands over which the Proterozoic seas at various times spread or transgressed, are frequently found at the bottoms of the great sedimentary series. Other great series of Proterozoic rocks of undoubted sedimentary origin are more or less metamorphosed to schists, quartzites, and crystalline limestones. The earliest Proterozoic sediments were derived from exposed portions of the Archeozoic, while later Proterozoic sediments may have been derived either from exposed Archeozoic or older Proterozoic. That the processes of sedimentation during the Proterozoic era were essentially the same as those of today is clearly proved by the very nature of the sediments, the typical stratification to even lamination, shallow-water marks, etc.

Associated with the great sedimentary deposits, more or less igneous rock occurs locally both as intrusions into the strata and as extrusions or lava-flows. Granite batholiths intruded the Proterozoic rocks at or near the close of the era.

In addition to the frequent metamorphism, the Proterozoic rocks have often been subjected to great deformative movements in the earth's crust so that the rocks have either been tilted or highly folded. Sometimes they have been infolded among the Archeozoic rocks.

## Distribution of the Proterozoic Rocks

Perhaps the largest Proterozoic area in North America is that in the Rocky Mountains of the northern United States and southern British Columbia. The well-known Lake Superior-Lake Huron district of Proterozoic is also of large extent. There are considerable areas in eastern Canada west of Hudson Bay, and smaller areas in Newfoundland, Nova Scotia, the Piedmont Plateau, at several places in the Mississippi Basin, Texas, Arizona (especially in the Grand Canyon), Nevada, eastern California, and at various places in the Rocky Mountain system of the United States and Canada.

Nearly all of the known outcrops of Proterozoic rocks occur within the areas of pre-Cambrian rocks shown in Figure 227.

### Subdivisions of the Proterozoic Group

In many regions where detailed studies have been made, the Proterozoic group may be subdivided into from two to four systems or series separated by distinct unconformities. In some places only one division has been recognized. At present no such subdivision into series or systems has a world-wide or even continent-wide application. Generally each of these divisions shows a thickness of at least a few thousand feet, while the whole Proterozoic group has a maximum thickness of many thousands of feet, or, according to some estimates, at least ten miles as in the Lake Superior district. These subdivisions or series of Proterozoic rocks will perhaps be best understood by briefly describing a few of the better known regions.

### Lake Superior–Lake Huron Region

One of the best and most carefully studied Proterozoic districts in the world is the Lake Superior-Lake Huron region. Proterozoic surficial rocks are there arranged in four distinct, largely sedimentary divisions separated from each other by unconformities, and named Lower Huronian, Middle Huronian, Upper Huronian (Animikian), and Keweenawan. At some localities not all of these divisions are represented. The relations of the divisions to each other and to the Archeozoic below and Paleozoic above are brought out in the accompanying tabular arrangement. As indicated by the unconformities, the deposition of each division was succeeded by emergence of the region accompanied by erosion, and this in turn followed by submergence accompanied by deposition of the next division. Such repeated changes of relative level between land and sea, as here recorded for Proterozoic time are among the most common and important phenomena of geologic history.

The *Huronian* rocks are principally gray and green quartzites, schists, slates, crystalline limestones, conglomerates, and beds of iron ore, all of which are more or less metamorphosed sediments. The original strata were largely laid down under water, probably sea water, but continental deposits are often prominent. Some igneous rocks, both intrusive and extrusive, are included in the Huronian system. The Lower and Middle Huronian are usually much more metamorphosed and folded than the Upper, the latter being at times scarcely at all deformed or metamorphosed. Estimates show the aggregate (maximum) thickness of the Huronian rocks to be no less than two or three miles.

| | | *Lake Superior-Lake Huron Region* |
|---|---|---|
| Paleozoic | | Cambrian or Ordovician strata |
| | | (Great unconformity) |
| Proterozoic | | Killarney granite. (Batholithic bodies) |
| | | Keweenawan system. (Volcanic and sedimentary rocks, with little or no metamorphism) |
| | | (Unconformity) |
| | Huronian system | Upper (Animikian and Whitewater) series. (Mainly sedimentary moderately metamorphosed) |
| | | (Unconformity) |
| | | Middle (Cobalt) series. (Mainly sedimentary, moderately metamorphosed) |
| | | (Unconformity) |
| | | Lower (Bruce) series. (Mainly sedimentary, much metamorphosed) |
| | | (Great unconformity) |
| Archeozoic | | Algoman granite |

A formation of unusual significance is a conglomerate or boulder clay, representing a thoroughly solidified glacial deposit, at the base of the Middle Huronian series. This deposit has been observed at many places within an area of thousands of square miles north of Lake Huron.

FIG. 232. Steep-dipping metamorphosed Huronian limestone (or marble). North Shore of Lake Huron. (Photo by T. T. Quirke for Geological Survey of Canada.)

The significance of this remarkably old glacial deposit is discussed beyond.

The *Keweenawan*, or latest Proterozoic system, is characterized by a great preponderance of lava beds which constitute the lower portion of the pile; are prominent in its middle portion; and are practically absent from the upper portion. Some idea of the stupendous and continuous volcanic activity of Keweenawan time may be gained from the fact that


FIG. 233. North-south structure section 45 miles long on the north side of Lake Huron. Vertical scale greatly exaggerated. *As* = Archeozoic schist; *Ag* = Archeozoic granite; *H* = Huronian strata (Bruce and Cobalt series, separated by unconformity) resting by unconformity upon Archeozoic rocks; black bands = Keweenawan basic intrusive igneous rocks; *K* = late Proterozoic (Killarney) granite; and *O* = Ordovician marine strata.
The principal events recorded in this section are as follows: Archeozoic schist intruded by much Archeozoic (Algoman) granite; profound interval of erosion; deposition of Bruce strata, erosional interval, and deposition of Cobalt series; intrusion of basic igneous rocks into the Cobalt strata; intense folding in late Proterozoic time; still later intrusion of the Killarney granite; long interval of erosion; and deposition of Ordovician strata in the sea. (Section modified after W. H. Collins, Geological Survey of Canada.)

lava sheets, mostly not over a hundred feet thick each, accumulated to a depth of at least three or four miles.

Toward the end of Proterozoic time, all Huronian rocks of the Lake Superior-Lake Huron region were more or less folded, and then intruded by batholiths of the so-called *Killarney* granite. Accompanying Figure 233 gives a good idea of the general relations of the Huronian rocks and their structures to the Archeozoic in the Huronian type region.

## Piedmont Plateau and New England

Rocks generally classified as of Algonkian (Proterozoic) age occur throughout the Piedmont Plateau of the eastern seaboard of the United States. They are particularly well exposed and best known from Maryland north to the vicinity of New York City, where they comprise several metasedimentary series, thousands of feet thick, intruded by plutonic rocks varying from granite to gabbro. In ascending order the principal

metasedimentary formations or series are quartzite, crystalline limestone (marble), and schist, with some intercalated beds of metamorphosed volcanics, all in conformable arrangement. They rest by unconformity upon Archeozoic rocks. An unconformity also separates them from overlying early Paleozoic (Cambrian) strata.

Proterozoic metamorphosed strata more or less similar to those of the Piedmont Plateau occur in western New England, but their classification and real extent have not yet been very definitely settled.

## Rocky Mountain Region

Perhaps the largest known single area of Proterozoic rocks in North America is that in the Rocky Mountains of the northern United States and southern British Columbia. These rocks generally rest upon eroded Archeozoic, and they are overlain unconformably by Cambrian or still younger strata. This unconformity may more precisely be called a disconformity because the Cambrian and underlying eroded Proterozoic strata usually have parallel or nearly parallel stratification surfaces. The rocks consist mostly of quartzites, sandstones, shales, and limestones, associated with remarkably little igneous rock. Their thickness is usually two to five miles. Some of the strata (in Montana) contain fossils. Thus far no satisfactory widespread subdivision of these rocks has been determined.

In Glacier National Park, Montana, a system of practically unaltered later Proterozoic strata, fully two miles thick, forms a vast block which has been thrust faulted over late Mesozoic strata (Fig. 299).

In the Belt Mountains of central-western Montana, a number of Proterozoic sedimentary formations, together called the *Belt system*, reach a total thickness of over 20,000 feet. The lower portion of this system has been metamorphosed into schist and quartzite, while the upper portion is mainly little altered shale, limestone, and sandstone. These rocks were notably folded, in part metamorphosed, and somewhat eroded before Cambrian strata were laid down upon them.

Farther south in the Rocky Mountains, metamorphosed Proterozoic strata often flank large bodies of Archeozoic rocks as in the Wind River, Big Horn, and Colorado Front Ranges. These strata usually show steep dips (Fig. 234). Similar strata are also well represented in the Uinta and Wasatch Mountains. Quartzites are common in most of the southern Rocky Mountain areas.

FIG. 234. Nearly vertical beds of Proterozoic quartzite on the east side of the Colorado Front Range. Thompson Canyon, Colorado. (Photo by W. T. Lee, U. S. Geological Survey.)

## GRAND CANYON OF ARIZONA

Far down in the Grand Canyon of the Colorado River, there are excellent exposures of Proterozoic rocks (the *Grand Canyon* system) with their relations to the Archeozoic and the Paleozoic well exhibited. The Archeozoic rocks, comprising granites, schists, and gneisses, were profoundly eroded before the immediately overlying Proterozoic rocks were deposited. The Grand Canyon system consists of two important

series. The lower one (*Unkar*), nearly 7,000 feet thick, is mostly sandstone and shale with some sills and lava-flows. The upper series (*Chuar*), separated from the lower by a slight unconformity, is over 5,000 feet thick, and it is made up of shales, sandstones, and limestones. Both series are tilted and faulted, and they are separated from immediately overlying marine Cambrian strata by a profound unconformity.

The Grand Canyon system must have been uplifted, tilted, and faulted, with production of block mountains, and then eroded to a condition of low relief, before submergence under the Cambrian sea. These historical facts are plainly indicated in Figure 235.

### California

In the White Mountains of middle-eastern California, there is a series of several stratified, somewhat metamorphosed formations consisting of dolomitic limestone, quartzite, sandstone, and slate, several thousand feet thick. These formations are considerably folded, and they lie unconformably below Lower Cambrian strata.

### Close of the Proterozoic (Killarney Revolution)

The Proterozoic era seems to have closed with North America all land, wider than at the present time, but not nearly so high on the average.

Canadian geologists have recently presented evidence to show that a mountain range at least 700 miles long, with a nearly east-west trend, was formed across middle Minnesota, northern Wisconsin and Michigan, and into southwestern Quebec. Late Proterozoic and older rocks were there folded, uplifted, and intruded by the Killarney granite before Cambrian strata were laid down upon the eroded edges of the Proterozoic. This range, called the Killarney Mountains, is probably the oldest known definitely located mountain range on the continent. Only the roots of it now remain.

It is quite certain that there were late Proterozoic upturnings and uplift of strata elsewhere, as in the Grand Canyon region of Arizona, but as yet we have no accurate data in regard to the dimensions and trend of the resulting mountains.

## Proterozoic Life

Some more or less determinable fossils have been found in Proterozoic strata, particularly in Montana and in the Grand Canyon of Arizona. They include algae, bacteria, worm tracks, sponge spicules, primitive brachiopods and fragments of crustaceans. Protozoan shells have been reported from the Proterozoic rocks of France. "The traces of pre-Cambrian (animal) life, though very meager, are sufficient to indicate that the development of life was well advanced long before Cambrian time began. . . . Stratigraphically, this fragment of what must have been a large fauna occurs over 9,000 feet beneath an unconformity at the base of the upper portion of the Lower Cambrian in northern Montana" (C. D. Walcott). More animal fossils are quite likely to be discovered, though the remains thus far found are those of very thin-shelled creatures and hence not so favorable for fossilization. Most animals of the time were probably without shells or other hard parts.

Walcott has described a number of species of limy algae from the Belt system of Montana. These algae were very simple, single-celled plants (thallophytes) which lived in water. They were hemispherical or cylindrical bodies which secreted crudely concentric layers of carbonate of lime from one to fifteen inches in diameter. They occur in distinct beds through hundreds or even thousands of feet of Proterozoic limestones. Well-pre-

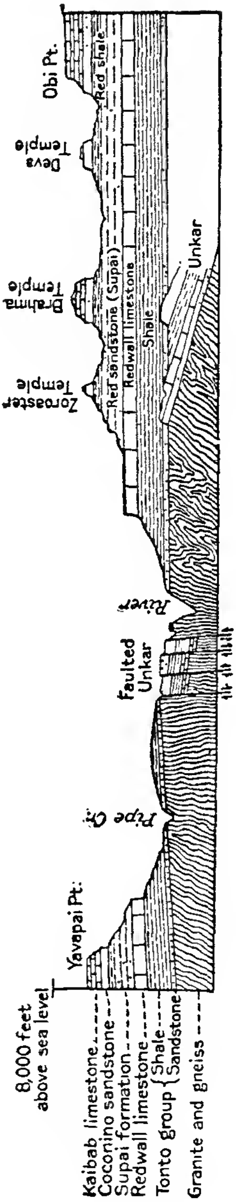



Fig. 235. *Structure section across the Grand Canyon of Arizona.* Granite and gneiss (or schist) are Archeozoic. Unkar is Proterozoic and Tonto to Kaibab are Paleozoic. (After N. H. Darton, U. S. Geological Survey.)

served algal remains occur in the upper limestone formation in Glacier National Park (Fig. 236). Similar fossils have also been found in the Grand Canyon system in Arizona.

Walcott has described what seem to be fossil bacteria (single-celled, tiny plants) from late Proterozoic rocks. Carbonaceous material, in-

FIG. 236. Concentric limy remains of a group of Proterozoic algae from Glacier Park, Montana. (Photo by Carroll L. Fenton.)

cluding graphite, so often disseminated through Proterozoic shales, and schists almost certainly indicate the presence of life. Likewise beds of limestone and bedded iron ores, so abundant in parts of the Proterozoic, are rarely ever known to have formed except through the agency of organisms.

### PROTEROZOIC CLIMATE

Since the great masses of Proterozoic sediments are of quite the usual sort like those formed in later eras, and since life surely existed, we can be certain that the climate of the time was favorable for the operations of ordinary geologic processes and hence not fundamentally different from that of comparatively recent geologic time.

The widespread occurrence of a glacial deposit at the base of the Middle Huronian series in Ontario has been mentioned. This deposit quite certainly shows that an ice sheet covered many thousands of square

miles of the area between Lake Huron and Hudson Bay. It is the earliest known record of glaciation. This proof of a climatic condition favorable for glaciation so early in the earth's history is indeed significant. It shows that the temperature and atmospheric conditions of the earth nearly a billion years ago was not fundamentally different from that of the present period of geological time.

What is believed to be glacial till of Proterozoic age has also been described from South Africa.

Very distinct evidences of glaciation in late Proterozoic time are known from various parts of the world, particularly in China, India, Norway, Greenland, Australia, and western North America. A few occurrences will be described briefly.

At the bottom of the thick section of Cambrian strata in China "on the Yangtse River, 31° Lat., i.e. as far south as New Orleans, not high above sea level, a large body of glacial material (170 feet thick) was discovered. . . . It demonstrates the existence of glacial conditions in a very low latitude in the early Paleozoic" (B. Willis).

At Lat. 70° N. in Norway, glacial deposits containing clearly striated pebbles have been found resting upon a distinctly smoothed and straited surface of hard rock.

In southern Australia glacial beds of similar age and considerable thickness are distinctly folded along with the enclosing strata.

Blackwelder has recently described a glacial deposit older than Middle Cambrian, and probably of late Proterozoic age, in the Wasatch Mountains of Utah.

It seems reasonable to associate the glacial conditions with the extensive uplifts and mountain-making in so many parts of the world when the higher general altitudes of the lands caused temperatures lower than normal in the various regions.

# CHAPTER XIX

## PALEOZOIC ROCKS AND HISTORY

### General Statement

The Cambrian represents the earliest period of the great Paleozoic era, and the rocks which make up the Cambrian system include the oldest known of the normal fossiliferous strata. Since these strata are the oldest which carry abundant organic remains, it follows that they are the earliest formed rocks to which the ordinary methods of subdividing and correlating rock masses can be applied. From the Cambrian on, the legible records of events of earth history are far more abundant and less defaced than those of pre-Cambrian time. From now on we shall be able to trace the changing outlines of the relief features of the continents and the evolution of organisms with some degree of definiteness and satisfaction, though a vast amount of work yet remains to be done both as regards discovery of new records and the interpretation of records old and new.

### Cambrian Period

**Cambrian Rocks.** On the accompanying map (Fig. 237) the surface distribution of Cambrian, Ordovician, and Silurian strata is shown, that is, the locations of the areas in which such strata are known to outcrop. The surface distribution of the rocks as indicated on this map gives no adequate idea of the former or present real extent of strata of the ages represented, since strata have either been removed from so many districts by erosion, or are concealed under later formations, or are highly folded so that outcropping edges only are at present visible. A fair idea of the minimum original extent of any system, or part of a system, of marine strata (e.g., Cambrian) may be gained from a paleogeographic map (e.g., Fig. 240) which shows the extent of the sea in which the strata were deposited.

The principal areas of Cambrian strata are in New England, southeastern Canada, New York, the Appalachian range, south of Lake Superior, southeastern Missouri, Oklahoma, central Texas, Nevada, east-

ern California, and at various places in the Rocky Mountain region.

Cambrian rocks consist very largely of shallow-water sediments such as conglomerates, sandstones (Fig. 238), and shales, with well-preserved ripple marks very common. Deeper or clearer water deposits such as limestone, are, however, important in the Appalachians, Vermont, Nevada, the Rocky Mountain region, and British Columbia. The thickness of Cambrian strata in North America generally varies from less than 1000 feet, in the Mississippi Valley, to a maximum of over 18,000 feet in the southern Appalachians. The Cambrian system shows maximum thicknesses of 9000 to 12,000 feet in Utah, eastern California, and the Canadian Rockies.

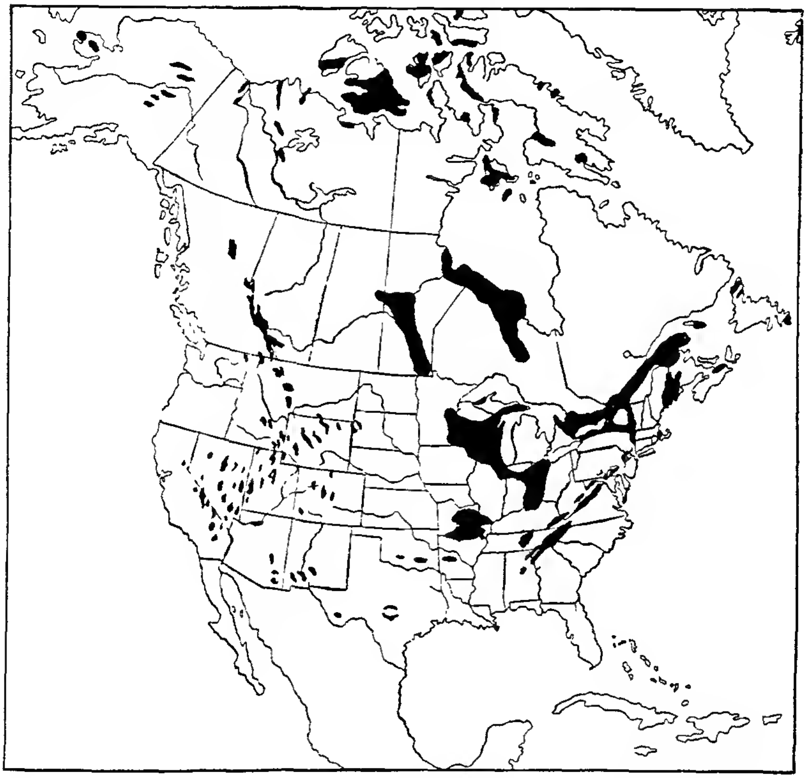


FIG. 237. Map showing known areas of outcrops (surface distribution) of Cambrian, Ordovician, and Silurian strata in North America.

North American Cambrian is singularly free from igneous rocks and thus presents a remarkable contrast with the preceding eras. Cambrian

strata are more or less metamorphosed in various regions as in the southern Appalachians, New England, and some of the mountains of the West.

**Cambrian History.** *Basal Unconformity.* We have already learned that a profound and seemingly almost universal unconformity separates the Archeozoic and Proterozoic rocks. Another great unconformity separates the Proterozoic and Paleozoic rocks. Cambrian strata seldom fail to rest upon the eroded surfaces of either the Archeozoic or the

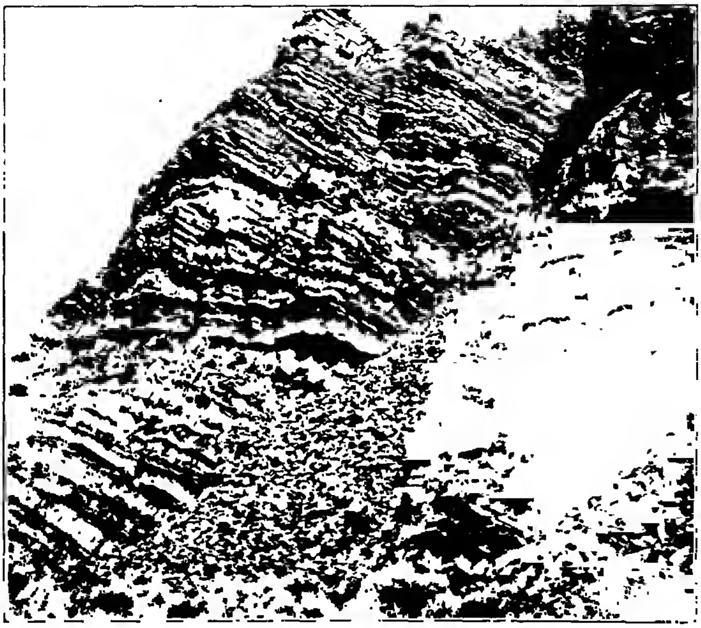


FIG. 238. Lower Cambrian strata at Deep Spring Valley, California.

Proterozoic. In many regions it has been shown that the Cambrian sediments not only rest upon an eroded surface of older rocks, but also that the surface of these latter had been worn down to the condition of a more or less well-developed peneplain. Accordingly, just before and during earliest Cambrian time, most, if not all, of North America must have been dry land suffering erosion. Conglomerates containing pebbles of the older rocks are of very common occurrence at the base of the Cambrian sediments. The great duration of this erosion interval which produced such a profound unconformity, not only in North America but in other continents as well, is regarded as one of the

greatest physical events of its kind in the history of the earth since late Proterozoic time.

*Cambrian seas.* During Early Cambrian time partial submergence of North America resulted in the development of two long narrow arms of the sea, one in the east and the other in the west, as shown on the accompanying map, Figure 239. These marked the beginning of

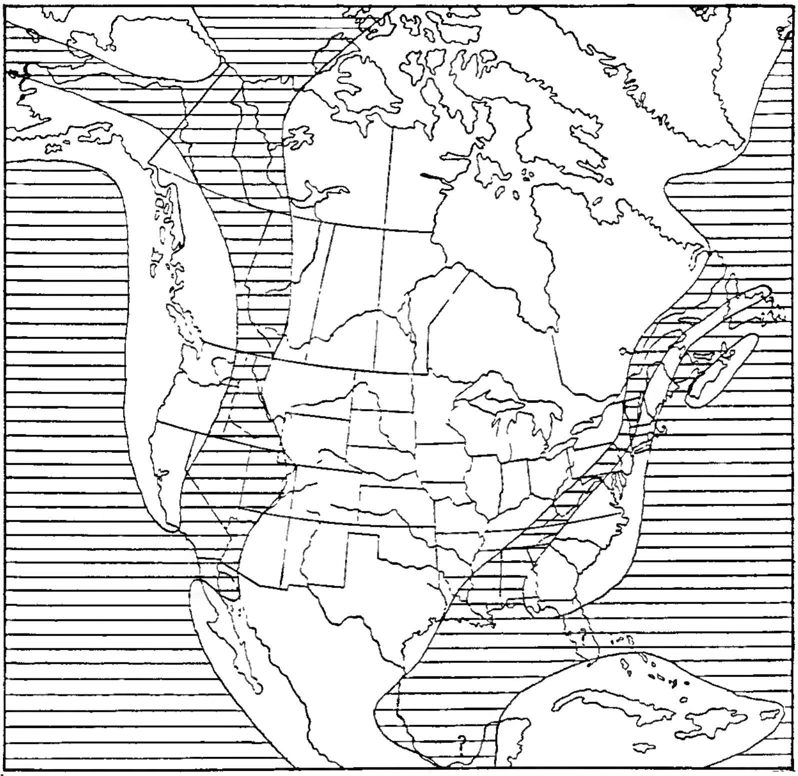


FIG. 239. Generalized paleogeographic map showing sea and land areas in North America during Early Cambrian time. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

the Appalachian and Cordilleran geosynclines, respectively, which were more or less persistent during early and middle Paleozoic times. As we have already learned, such a submergence may have been produced either by rising sea level or subsidence of the land, or both. In the case of the Cambrian submergence there appears to be no escape from the conclusion that a rise of the sea was an important factor, because the

development of the extensive peneplain surface above mentioned implies that the continent must have remained almost unaffected by diastrophic movements for a long time, and the tremendous volume of material removed and dumped into the sea must have very appreciably raised its level.

Wherever Lower Cambrian marine strata (actually exposed or concealed) rest directly upon pre-Cambrian rocks we can be sure that such areas were submerged under the Early Cambrian sea, because Lower Cambrian strata could have formed only during that time. To these areas must be added still others from which once present Lower Cambrian rocks have been removed by erosion. Again, many large areas were almost certainly dry land during Early Cambrian time because there is not the slightest evidence of any sort that deposition went on over those areas during that time. The principles here set forth are of fundamental importance in constructing a paleogeographic map of North America for Early Cambrian time, and the same principles must be kept in mind in considering the paleogeography of any given region during any succeeding time.

A considerable withdrawal of the eastern arm of the sea (especially in the north) marked the close of Early Cambrian time, but the western sea (or mediterranean) became somewhat larger, especially from Idaho eastward. This was the condition of the continent during Middle Cambrian time.

During Late Cambrian time more and more of the continent tended to become submerged until the geographic conditions were much as depicted upon the next paleogeographic map (Fig. 240). The sea transgressed northward over the great interior land to about the northern border of the United States, forming a vast interior sea. Fully one-third of the continent was flooded. As the map shows, there were six large land areas—Appalachia, Antillia, Canadia, Cascadia, Siouxia, and Mexicoia. These six land areas, with somewhat changing borders, were remarkably persistent during the repeated early and middle Paleozoic flooding of the continent.

The northward transgression of this great interior sea in the eastern United States is clearly established by the fact that studies of actual outcrops and deep well sections show successively younger and younger Upper Cambrian sediments deposited by overlap northward upon the pre-Cambrian rock surface. We also know that this interior sea was shallow because of the nature of the sediments which are very largely clastic such as sandstones and shales, often ripple marked, and with con-

glomerates at the base. Some heavy limestone beds like those in eastern New York, and between Virginia and Missouri, tell of clearer, possibly deeper, water in those places.

*Close of Period.* Throughout Cambrian time, and even at its close, North America was not affected by any really great physical disturbances such as mountain-making or igneous activity.

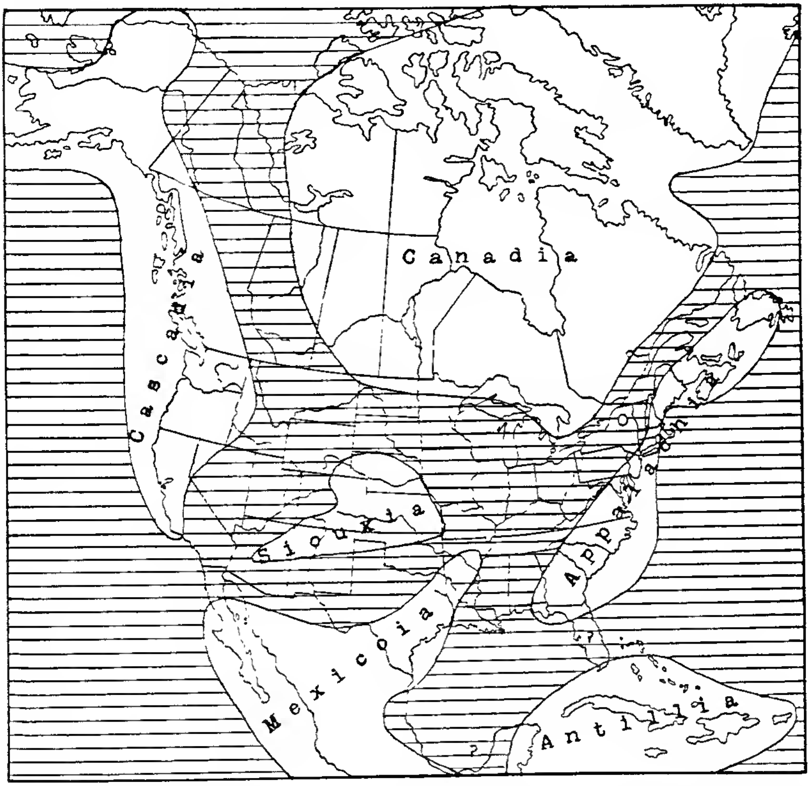



FIG. 240. Generalized paleogeographic map showing sea and land areas in North America during Late Cambrian time. This was the greatest Cambrian sea. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

A belt extending from Vermont to northern New Brunswick was considerably elevated, probably without much folding, at the close of the period as proved by a conglomerate of early Ordovician age resting upon the disturbed and eroded late Cambrian strata. This has been called the *Vermont Disturbance*.

According to Schuchert the Cambrian period closed with "a very wide and probably complete retreat of the epeiric (continental) seas from the interior parts of North America, leaving the continent all or nearly all dry land." Millions of years of erosion had reduced the lands of the continent to low level with little relief.

**Cambrian Climate.** We have already learned that comparatively high lands, with accompanying glaciation, marked the closing stages of the Proterozoic era in many parts of the world. Very early in the Cambrian period, however, the lands were generally lower, and glacial conditions no longer existed.

The character and widespread distribution of many of the organisms of the time (especially those which secreted lime from sea water) throughout low and high latitudes, and also the conditions favorable for ordinary processes of weathering, erosion, and deposition of sediments, indicate that the climate of Cambrian time was not essentially different from that of comparatively recent geological time, but that climatic conditions were then much more uniform over the earth than now.

## Ordovician Period

**Ordovician Rocks.** Most of the regions indicated in black in Figure 237 contain large or small areas of outcrops of Ordovician strata, thus showing the remarkably widespread surface distribution of strata of this age. It is also a significant fact that most of the widely distributed Ordovician strata by far were laid down under sea water.

The surface distribution of Cambrian and Ordovician strata is much the same except for the presence of Ordovician and lack of Cambrian in the Arctic Islands, Hudson Bay region, and the large area southwest of Hudson Bay. Viewed in a broad way, the Ordovician rocks (especially the Lower and Middle) are of different nature from those of the Cambrian. Clastic sediments, such as conglomerates, sandstones, and shales, are the dominant Cambrian sediments, while, throughout the Lower and Middle Ordovician, limestones greatly predominate. Mid-Ordovician is generally regarded as having been one of the greatest limestone-making times in the earth's history, the Trenton and Black River formations being especially widespread (Fig. 241). The *Trenton* limestone may be especially mentioned as a remarkable example of a relatively thin formation of very great extent. It is seldom more than 500 feet thick; it consists very largely of highly fossiliferous marine limestone; and it once existed as a single, unbroken sheet of rock over an

area of several hundred thousand square miles of the New York-Appalachian Mountain-Interior Lowland region. Much of the original rock is still left at the surface or under cover of later rocks.

The aggregate thickness of Ordovician strata in New York is from 2000 to 4000 feet; in the Appalachian Mountains, 5000 to 8000 feet; in the central Mississippi Valley (e.g. Missouri), 1000 feet or less;

FIG. 241. Trenton limestone (thin-bedded) resting upon massive Black River limestone near Boonville, New York.

in the Rocky Mountains several thousand feet; and in eastern California, 5000 feet.

In parts of New England and the western United States, Ordovician strata are often notably metamorphosed.

Igneous rocks are very little represented in the Ordovician system of North America. Plutonic rocks are practically unknown, but a re-

markable occurrence is that of several thin beds of Middle Ordovician volcanic ash known within an area of several hundred thousand square miles of the Appalachian region and eastern Interior Lowland. Middle Ordovician volcanic rocks occur in abundance in Newfoundland and more locally in a part of eastern Quebec.

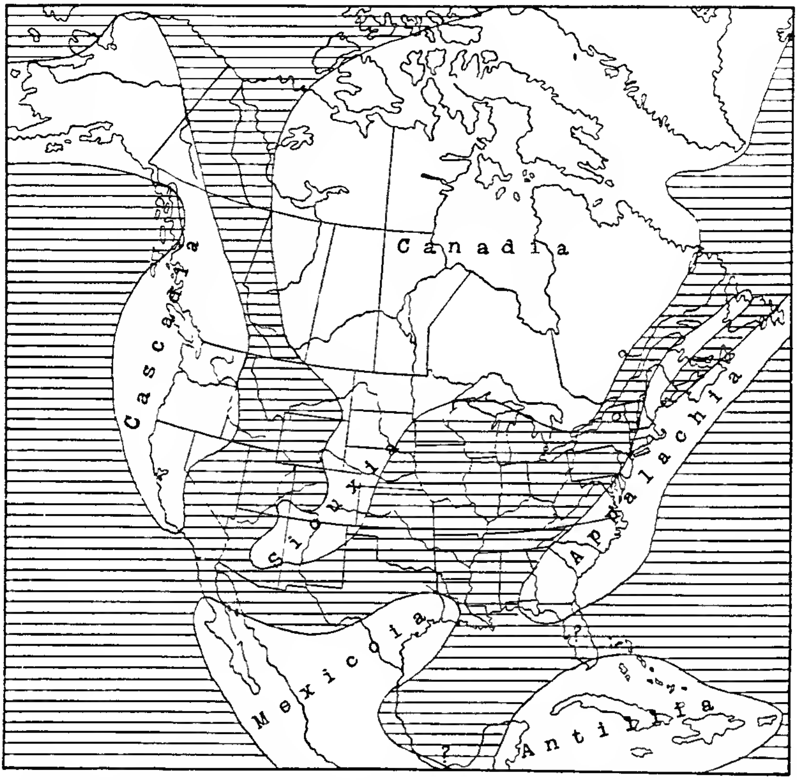



Fig. 242. Generalized paleogeographic map showing sea and land areas in North America during Early Ordovician time. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Schuchert and A. Grabau.

**Ordovician History.** *The Seas.* After the extensive emergence which caused practically all of North America to be a land area at the close of the Cambrian, the sea began, in Early Ordovician time, to encroach upon portions of the continent. By the middle of the Early Ordovician marine waters overspread the areas shown on the accompanying map (Fig. 242). Early Ordovician time seems to have closed with a general disappearance of the marine waters from North America.

The outstanding feature of the Middle Ordovician physical history was the greatest known invasion of the continent by marine waters. Beginning with the continent dry land, the sea more or less gradually spread until the midst of Middle Ordovician time when the grand climax was reached as shown by Figure 243. At least two-thirds of the

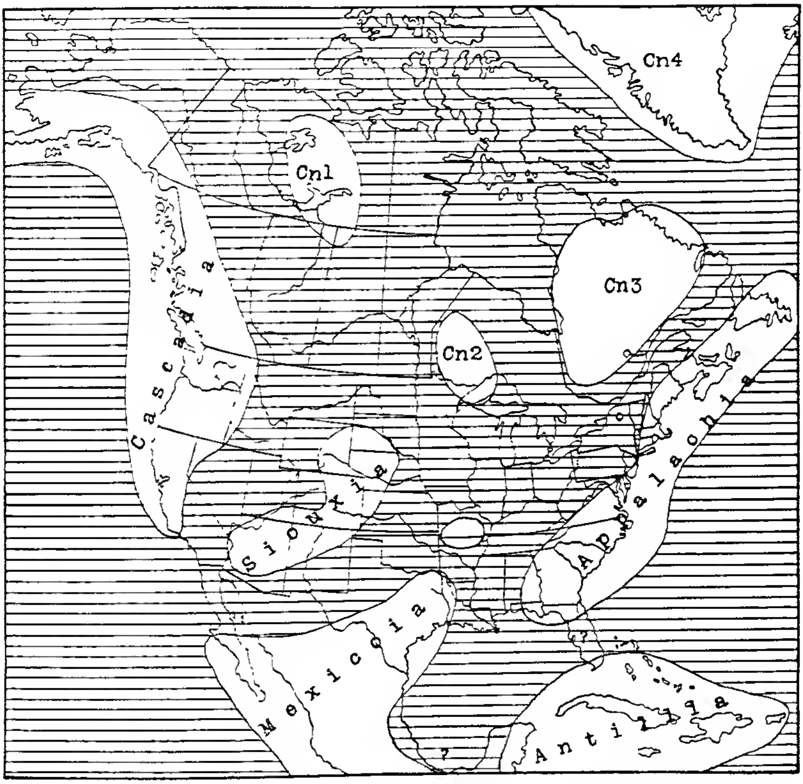



FIG. 243. Generalized paleogeographic map showing sea and land areas in North America during Middle, and also during Late, Ordovician times. These were the greatest known seas in the history of the continent. White areas, land; ruled areas, sea. Cn 1, 2, 3 are parts of Canadia. Principal data (modified) from maps by B. Willis, C. Schuchert, and R. Chamberlin.

continent was submerged. The lands were low, erosion was not very active, the seas were wide, and, therefore, relatively little land-derived sediment was deposited on the floor of the widespread continental sea. It was, rather, a time unusually favorable for limestone making, and the remarkably extensive Trenton limestone was then formed. This vast

sea teemed with invertebrate forms of life, including thousands of species.

The close of Middle Ordovician time was marked by a withdrawal of the marine waters from all of the continent excepting the general Appalachian Mountain area and westward to Michigan and Arkansas.

Late Ordovician time was marked by a renewed great transgression of the sea which was almost as extensive, and covered nearly the same areas, as the vast Middle Ordovician sea. This widespread sea existed during the midst of Late Ordovician time.

*Close of the Ordovician (Taconic Revolution).* The Ordovician ended with important physical or crustal disturbances, including mountain-making. All, or nearly all, of the great interior (epeiric) sea appears to have been drained as a result of change in level between land and sea at the close of Ordovician time. In the interior of the continent the land was only moderately elevated to remain dry until the early part of the next period.

Thousands of feet of Cambrian and Ordovician strata accumulated in the seas which covered eastern New York, the sites of the Green Mountains and Berkshire Hills of western New England, eastern Pennsylvania, and possibly as far south as northern Virginia, including part of the Piedmont Plateau area. Toward the close of the Ordovician period, a great compressive force was brought to bear in the earth's crust upon this mass of strata. As a result of the compression, the strata were tilted, folded, and elevated above sea level into a mountain range which has been called the Taconic Range, and the physical (orogenic) disturbance has been called the *Taconic Revolution.* In structure, the range consisted of a series of folds, both great and small, whose axes were parallel to the main axis of the range, that is north-northeast by south-southwest. Though we have no way of telling just how high the range may have been, nevertheless the structural features and the vast amount of erosion since the folds were produced clearly indicate that the uplift was at least some thousands of feet.

How do we know that the Taconic disturbance took place toward the close of the Ordovician period? Strata of the next succeeding period (Silurian) rest directly in places upon the eroded edges of Late Ordovician rocks; hence it is obvious that the disturbance occurred before the Silurian strata were deposited (Fig. 244). Also the disturbance doubtless began before the close of the Ordovician period. This is borne out by the fact that, for example, in central New York a distinct eroded surface at the top of rather late Ordovician shales proves that region to have been dry land before the end of the period, this uplift quite certainly

having been produced by the early movements of the Taconic Revolution.

In New Brunswick, Silurian strata rest upon the eroded edges of upturned Ordovician strata, and this upturning may have been coincident with the Taconic disturbance.

Sufficient lateral pressure was brought to bear in a portion of the Mississippi Basin, during the latter part of the period, to produce a long,

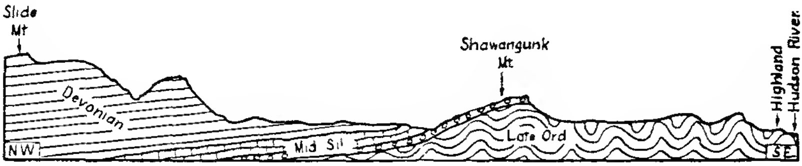



FIG. 244. Structure section through part of southeastern New York showing how the Late Ordovician strata were folded (Taconic Revolution) and eroded before the Silurian strata were laid down nonconformably upon them. The Silurian strata were deformed at a much later time.

very low arch in the rocks from southern Ohio into Tennessee. This has been called the "Cincinnati Anticline."

**Ordovician Climate.** Red sandstone, salt, and gypsum in the Upper Ordovician of northern Siberia clearly imply an arid climate in northern Asia during the late Ordovician. So far as can be determined from the character of the rocks, geographic conditions, and distribution of the fossils, the climate of North America and Europe must have been mild and much more uniform than now. Ordovician fossils even from Arctic lands, are very similar to those of low latitudes.

The very extensive Ordovician seas, allowing a much freer circulation of waters between low and high latitudes, no doubt helped to keep the climate of the earth more uniform then than at the present time.

## SILURIAN PERIOD

**Silurian Rocks.** As in the case of the Ordovician system, most of the regions indicated in black in Figure 237 contain large or small areas of outcrops of Silurian strata thus showing their remarkably widespread surface distribution. Most of the areas of outcrops by far lie in the eastern one-half of North America, mainly in the Appalachian Mountain, Interior Lowland, New York, Great Lakes, Gulf of St. Lawrence, Hudson Bay, and Arctic Island regions. Comparatively few, small, scattered areas occur from the Rocky Mountains westward. Certain points

of comparison with the distribution of the Ordovician may be mentioned. Thus to a very considerable degree the Silurian and Ordovician rocks occur in the same areas, the chief differences being much more extensive areas of Silurian strata in the Arctic Islands region, their almost complete absence from the upper St. Lawrence Valley, and their much smaller representation in the mid-Mississippi Basin, Rocky Mountains, and Great Basin of the west.

The Silurian strata are, broadly considered, much like the Ordovician. They are very largely shales, sandstones, and limestones of marine origin and often in formations of wide extent. Mention may be made of two formations of special interest—the *Clinton* of Middle Silurian age, and the *Salina* of the Upper Silurian. These are widely developed in the Mississippi Basin and Appalachian regions. The Clinton formation nearly everywhere contains interstratified beds of iron ore (hematite), and salt beds of great commercial value are almost invariably associated with the Salina formation.

From central to western New York the thickness of the Silurian system is from 2000 to 3000 feet. Its usual thickness is from 2000 to 6000 feet in the Appalachians, while in the Mississippi Valley the thickness is generally less than 1000 feet. In Maine the Silurian system contains 6000 feet of strata and thousands of feet of volcanic rocks. A thickness of about 1000 feet of Silurian occurs in central Utah, and 2500 feet in Alaska.

Plutonic rocks of Silurian age are practically unknown in North America, but volcanic rocks—both lavas and tuffs—occur in great abundance in parts of Maine, New Brunswick, and Nova Scotia.

More or less metamorphosed Silurian strata occur in some places as in parts of New England and the western mountains.

**Silurian History.** *The Seas.* As a result of physical disturbance toward the close of the Ordovician, much of the interior Paleozoic sea was drained, causing the land area to be so much enlarged that it was as extensive as at any time since the beginning of the Paleozoic era. This was essentially the geographic condition of the continent at the beginning of the Silurian. The boldest topographic feature was the presence of the newly formed Taconic Range along the Atlantic seaboard.

During Early Silurian time there was a more or less gradual encroachment of the sea until in the later Early Silurian time when about one-third of the continent was flooded. Most of the eastern one-half of the continent, excepting Appalachia, Antillia, and eastern Canada, was

covered by a shallow sea extending from the Gulf of Mexico to the Arctic Ocean, with an arm through the St. Lawrence Valley region to the North Atlantic Ocean. Coarse Early Silurian sediments derived from the young Taconic Mountains and rejuvenated Appalachia, were


FIG. 245. Generalized paleogeographic map showing sea and land areas in North America during Middle Silurian time. This was the greatest Silurian sea. White areas, land; ruled areas, sea. Small circles show volcanoes in Maine, New Brunswick, and Nova Scotia. Principal data (modified) from maps by C. Schuchert and R. Chamberlin.

laid down in this sea from New York to Alabama, while finer sediments and limestones were deposited farther west.

The Early Silurian seas of western North America were far more restricted, but their extent is at present rather imperfectly known. An arm of the Pacific Ocean probably extended across southern California and Nevada into southern Idaho.

At the close of Early Silurian time the seas largely withdrew from the continent.

In Middle Silurian time a grand marine invasion set in, reaching a climax in late Middle Silurian time. This was one of the four or five most extensive floods in the known history of North America. The general relations of land and water, about as shown on map Fig. 245, were much like those of Middle Ordovician time with the exception of the much larger Silurian land area (Siouxia) in the interior of the continent More than one-half of North America was covered. This vast sea was a shallow-water epeiric sea teeming with invertebrate animals.

That a very appreciable retrogression of the Middle Silurian sea ushered in Late Silurian time is proved by both the comparatively restricted distribution and the character of the Salina formation. Thus in the eastern United States and Canada, Salina strata occur only through parts of Pennsylvania and southward to Virginia in the Appalachians, parts of New York, southeastern Ontario, Ohio, and Michigan, and they are quite generally characterized by red shales and sandstones, and by salt and gypsum deposits. Such materials imply arid climate conditions, with deposition in extensive lagoons or more or less cut-off arms of the sea, rather than typical open sea conditions. At the same time arms of the sea existed in the St. Lawrence Basin, and probably across southern California and Nevada.

A very late Silurian sea spread from eastern New York westward over the Salina lagoon areas and into eastern Wisconsin, and from eastern New York southward through the Appalachian district. The St. Lawrence and California-Nevada arms of the sea still persisted. As far as known the rest of the continent was dry land.

*Close of the Silurian.* At the close of the Silurian, or opening of the Devonian, the Silurian sea withdrew from the area from central New York to Wisconsin, and but few comparatively small areas of North America remained submerged.

There appear to have been no mountain-making (orogenic) movements, and no important epeirogenic disturbances at the close of the Silurian in North America. Because of the comparatively quiet and gradual transition into the succeeding period, the Silurian and Devonian systems are usually not sharply separated from each other, and often, as in New York and in the Appalachian region, there has been difficulty in satisfactorily dividing the systems.

**Silurian Climate.** The general distribution and character of the rocks and their fossil content point to more uniform climatic conditions

than those of today. Fossils in the Arctic Silurian rocks are not essentially different from those of low latitudes.

From central New York across to Michigan at least, there was an arid climate during the Salina epoch, as already mentioned, but this was probably only local.

## Devonian Period

**Devonian Rocks.** All known areas of outcrops of Devonian strata in North America occur within the regions showing the surface distribution of Devonian, Mississippian, and Pennsylvanian strata as indicated by map, Figure 247. As in the case of the earlier Paleozoic strata (Fig. 237), and for reasons already stated, so here the map (Fig. 247) shows by no means the full extent, present and past, of the strata. A comparison with the Silurian shows that, in the eastern part of the continent, these two rock systems are very similar in distribution, though the Devonian is absent from Newfoundland and is of much larger extent in New York. The only other important differences are a much larger Devonian area in the Mackenzie River region and much smaller areas in the Arctic Islands region.

Devonian strata are very largely marine limestones, shales, and sandstones, formations of which are often of wide extent. The Devonian system in New York is remarkably complete, widely exposed, and but little disturbed from its original condition.

Two of the most interesting Devonian formations are the *Onondaga* and the *Catskill.* The Onondaga limestone formation of mid-Devonian age extends from eastern New York and Pennsylvania westward to northern Michigan and southern Illinois. Its thickness is seldom over 200 feet, and it is often largely made up of corals, as for example at the Ohio River rapids near Louisville. In northern Maine, New Brunswick, and Nova Scotia, the Onondaga limestone is widespread and apparently many hundreds of feet thick. It also occurs at the south end of Hudson Bay. The Catskill formation of southeastern New York and eastern Pennsylvania is largely sandstone of shallow-water, nonmarine origin, 1500 to 8000 feet thick. It is probably a great delta deposit, as pointed out beyond.

In the northern Appalachian Mountains the Devonian system attains a maximum thickness of some 14,000 or 15,000 feet. In the southern Appalachians the thickness is usually less than 1000 feet. In New York state the system has a thickness of 4000 to 7000 feet. Over much

of the upper Mississippi Valley the thickness is generally less than 1000 feet, though rather locally, in Ohio, a thickness of fully 3000 feet is reached. In Nevada the system appears to show 6000 feet of limestone and shale. In Utah the system reaches a thickness of about 5000 feet.

Both plutonic and volcanic rocks of Devonian age occur in considerable quantities in parts of New England, New Brunswick, Nova Scotia, and southeastern Quebec. Their emplacement accompanied the

FIG. 246. An anticlinal fold in Silurian strata in the Appalachian Mountains. The conspicuous beds are sandstone. Near Clifton Forge, Virginia. (Photo by J. S. Grasty.)

later Devonian mountain-making described beyond. Devonian lavas occur in northern California.

In parts of New England and north to the Gulf of St. Lawrence, and also in some places in the mountains of western North America, Devonian strata have been more or less metamorphosed.

**Devonian History.** *The Seas.* In earliest Devonian time most of North America appears to have been dry land. Inspection of the paleogeographic map (Fig. 248) of that time shows that marine waters occupied a long, narrow area in the east. This sound covered the sites of the Appalachian Mountains, western New England, and the St. Lawrence Basin, connecting the last named region with the Gulf of Mexico. It was much like the Early Cambrian sound in the same region. In the west, an arm of the sea reached across parts of Cali-

fornia, Nevada, Utah, Idaho, and western Montana. Parts of southern Alaska and the Arctic Islands region were submerged.

An outstanding feature of North American Devonian history was the more or less steady advance of marine waters from the beginning of the period to beyond the middle. This marine invasion, first in the east and then in the west, reached a grand climax in late Middle De-

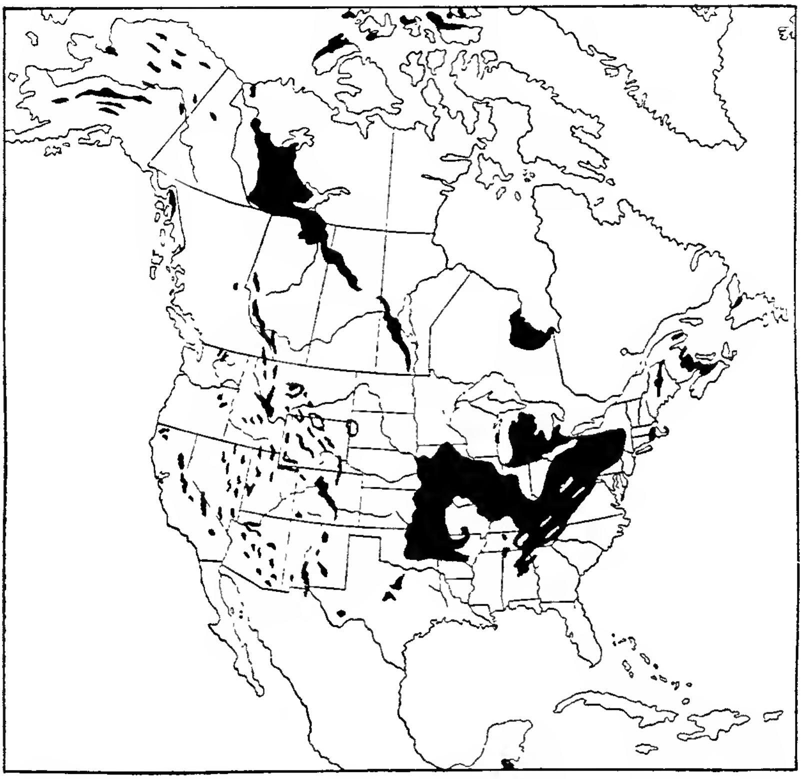


FIG. 247. Map showing known areas of outcrops (surface distribution) of Devonian, Mississippian, and Pennsylvanian strata in North America.

vonian (or Hamilton) time when fully 40 per cent of the continent was submerged as shown by map, Figure 249. This was one of the five or six greatest known floods in the history of North America. It should be noted that Appalachia and Canadia were connected across New England and the Upper St. Lawrence Basin.

The great sea which was so extensive in the late Middle Devonian continued to cover nearly the same areas in early Late Devonian time.

Then the sea began to retire from the land, first from the east and finally from the west, leaving the whole continent, as far as we know, dry land at the close of the period.

In New York and the northern Appalachian region, there was a tremendous accumulation of sandstone together with more or less shale and conglomerate. This Catskill formation, as already stated, is largely

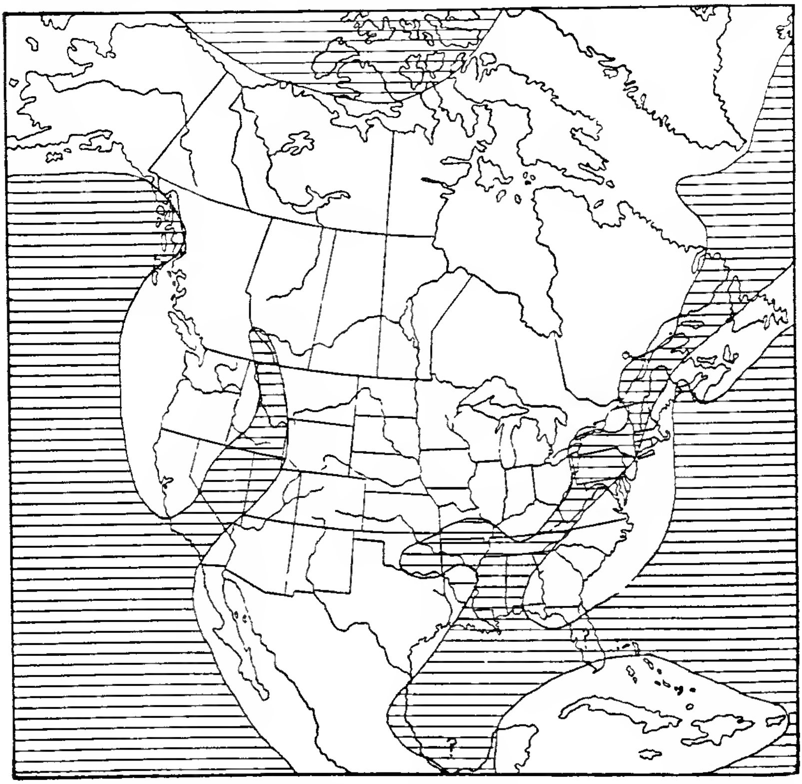


FIG. 248. Generalized paleogeographic map showing sea and land areas in North America during Early Devonian time. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Schuchert.

a shallow-water, non-marine deposit from 1500 to 8000 feet thick in New York and Pennsylvania. The few known fossils are non-marine types. This, together with the common occurrence of red shales and sandstones, and the great thickness of the beds, all point to the origin of this remarkable formation as either a great delta deposit pushed out into the shallow interior sea, or as an estuarine or lagoon deposit.

Notable thinning toward the west proves the material to have come from the east, doubtless from greatly rejuvenated Appalachia. Farther westward, over Michigan, Indiana, and Tennessee, the deposits formed

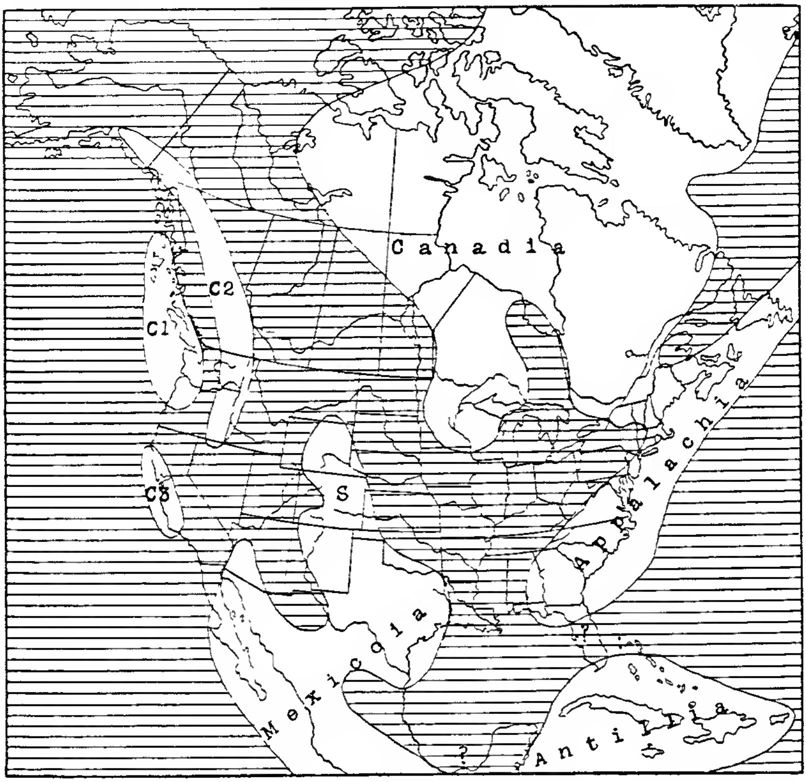



FIG. 249. Generalized paleogeographic map showing sea and land areas in North America during late Middle and early Late Devonian times. This was the greatest Devonian sea. White areas, land; ruled areas, sea. C1, C2, and C3 are parts of Cascadia, and S is Siouxia joined to Mexicoia. Principal data (modified) from maps by B. Willis, C. Schuchert, and R. Chamberlin.

at the same time were mostly shales, usually not over a few hundred feet thick.

*Close of the Devonian (Acadian Revolution).* Real mountain-making is known to have taken place in only one region, namely, through eastern New England, New Brunswick, Nova Scotia, and Newfoundland. This has been called the *Acadian Revolution.* The movement of folding and elevation, accompanied by igneous activity (both plutonic and volcanic), began well before the end of the period and reached a

climax near its close. Succeeding Mississippian strata rest by unconformity upon the more or less upturned and eroded rocks of the region.

The rise of the Acadian Mountains no doubt so rejuvenated northern Appalachia that a large stream from it produced the great Late Devonian delta above described.

**Devonian Climate.** The widespread distribution and the character of many of the fossils, as, for example, the corals which lived in the Middle Devonian sea, indicate rather mild and uniform climatic conditions. There were local conditions of aridity, and glacial deposits have been reported from South Africa.

## Mississippian Period

**Mississippian Rocks.** Strata of this age are abundantly represented within most of the areas of outcrops shown by Figure 247. In the western part of the continent the Mississippian and Pennsylvanian systems often have not been satisfactorily separated. In the eastern part of the continent, however, the two systems have usually been clearly separated. A comparison with the Devonian shows that the Mississippian has a very similar surface distribution in eastern North America, and that the Mississippian generally borders the Devonian areas. This is because Devonian conditions gave way to Mississippian with no great interruption of deposition.

A distribution feature of special importance as compared with the Ordovician, Silurian, and Devonian is the complete absence of Mississippian strata from all of the northern one-half of North America east of the Rocky Mountains with the exceptions of the Gulf of St. Lawrence and Arctic Islands regions.

Most of the Mississippian strata of North America are ordinary marine limestones, sandstones, and shales, but there are considerable formations of non-marine origin. Two of the latter are the *Pocono* sandstone of Lower Mississippian age, and the *Mauch Chunk* shale of Upper Mississippian age. The Pocono sandstone, including some thin beds of coal, extends from northern Pennsylvania to Virginia in the Appalachian Mountains. It contains numerous terrestrial fossils, hence it is not a true marine deposit. The Mauch Chunk red, sandy shale also occurs in the northern Appalachian district. It is either a great flood-plain or delta deposit. The Upper Mississippian *St. Louis* limestone formation is very widespread in the upper Mississippi River States.

The Mississippian system in eastern North America ranges in thick-

ness from about 5000 feet in eastern Pennsylvania to only some hundreds of feet in the western part of the same state. In the Mississippi River states the maximum thickness is 2500 feet, though it is generally less than 1000 feet. The Ouachita Mountains contain shales and limestones about two miles thick. In the western part of the continent thicknesses of several thousand feet (maximum over 5000 feet) have been observed at several places, while in other localities, as in the Black Hills and parts of Colorado, it measures only a few hundred feet thick. Five hundred feet are known in the Grand Canyon of the Colorado River.

In Nova Scotia and New Brunswick the thickness of the Mississippian strata reaches fully 5000 feet.

There is little evidence of Mississippian igneous activity in North America. Some beds of tuff occur in Upper Mississippian strata in the Ouachita Mountains.

The Mississippian strata in southeastern New England, in the Sierra Nevada Mountains (Calaveras formation), and in some other parts of the west are more or less metamorphosed.

**Mississippian History.** *The Seas.* The continent was all, or nearly all, land at the opening of the Mississippian period. Disregarding certain minor shiftings of the sea, the great event of Early Mississippian time was an increasing expansion of the sea over the land until late Early Mississippian time when about one-third of the continent was submerged. Figure 250 shows the general relations of land and water of that time. Much of the area of the United States was covered by an unbroken expanse of shallow sea water with wide connections with the Pacific and Arctic Oceans and the Gulf of Mexico. Canadia was very large and connected with Appalachia across New England. Cascadia and Mexicoia were well-defined as such. "Red Beds" with associated salt and gypsum beds were deposited in the Michigan region.

In the midst of the period there was a very considerable withdrawal of the sea, moderate in the east, but almost complete in the Rocky Mountain region.

During Late Mississippian time there was a tendency for the waters again to spread over the late Early Mississippian areas, but not so extensively. Thus the middle and middle-northern parts of the United States were not submerged, and the sea was more restricted over the site of the Rocky Mountains, extending over the northern portion of the latter region only in the Late Mississippian if at all.

*Close of the Mississippian.* (*Ouachita Disturbance.*) The complete emergence of the continent at the close of the Mississippian was accom-

panied by some folding or tilting of the strata. In certain regions there were actual mountain-making movements, though not on a large scale. Thus, a nearly east-west zone through Arkansas and Oklahoma, where a thick body of strata had accumulated during five periods of the Paleozoic, was subjected to pressure, considerably folded, and uplifted into

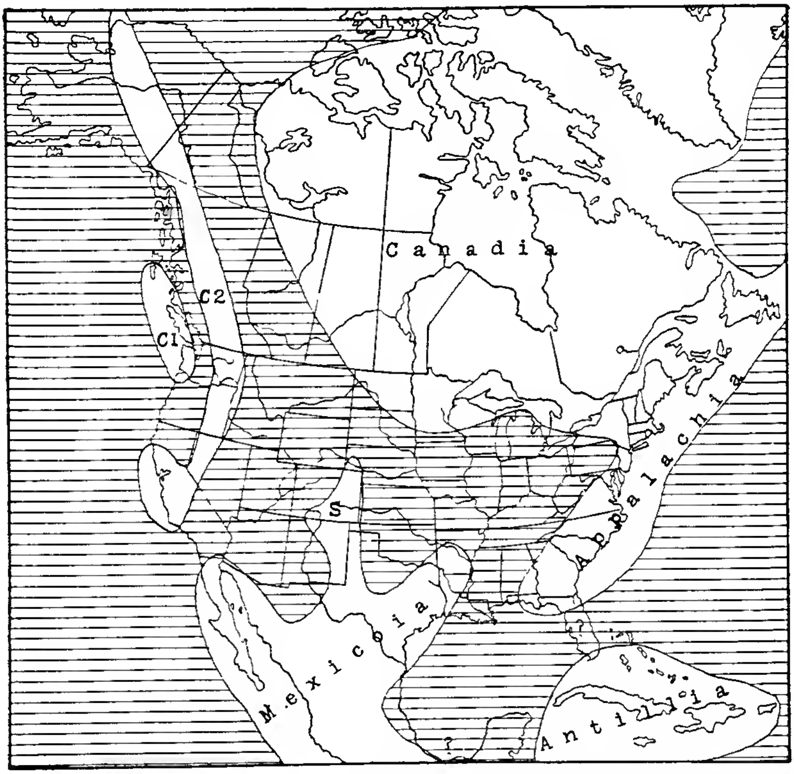



FIG. 250. Generalized paleogeographic map showing sea and land areas in North America during late Early Mississippian time. This was the greatest Mississippian sea. C1 and C2 are parts of Cascadia, and S is a remnant of Siouxia connected with Mexicoia. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Schuchert and J. Weller.

mountains. This involved the Ouachita and Wichita Mountains of Arkansas and Oklahoma, and hence has been called the *Ouachita Disturbance*. The Ouachita Revolution occurred later.

Mississippian and older rocks in parts of Nova Scotia and New Brunswick were also notably folded and elevated as proved by the fact that Pennsylvanian strata there rest upon upturned, eroded edges of

Mississippian and older rocks. The newly exposed lands of the continent were notably eroded, and the Mississippian and Pennsylvanian systems are separated by one of the most extensive and distinct unconformities in the whole Paleozoic group of rocks. For this reason the Mississippian and Pennsylvanian should be regarded as separate systems rather than as merely subdivisions of the old Carboniferous.

**Mississippian Climate.** As for the earlier Paleozoic periods, the character and distribution of Mississippian fossils rather clearly prove absence of well-defined climatic zones like those of today. A mild, uniform climate appears to have prevailed. Salt and gypsum beds more or less associated with "Red Beds" point to arid climate in Michigan, Montana, Nova Scotia, and Australia, but these were probably local conditions.

## Pennsylvanian Period

**Pennsylvanian Rocks.** Only in the eastern part of the continent have the Mississippian and Pennsylvanian rocks been satisfactorily separated. Pennsylvania strata are very extensively developed in eastern North America within the areas represented in black in Figure 247.

Pennsylvanian strata show in numerous places in western North America from northern Mexico to central Alaska, particularly in the western interior of the United States within the areas indicated on the map (Fig. 247). Rocks comprising this system in the eastern part of North America are partly of marine and partly of non-marine origin with the latter (including coal) unusually well developed.

There are four well-known subdivisions of the Pennsylvanian system in the Appalachian district. The formation names, character, and thickness of these subdivisions are typically illustrated by Figure 252. The greatest coal beds occur in the Allegheny and Monongahela.

Small areas of Pennsylvanian igneous and metamorphosed sedimentary rocks, together with some graphitic coal, occur in Rhode Island and Massachusetts.

Coal-bearing strata of this age, largely shales and sandstones of non-marine origin, attain a thickness of thousands of feet in New Brunswick and Nova Scotia.

In the midst of the Mississippi Basin, especially from Indiana westward to eastern Nebraska and thence southward into Texas, alternating, continental, coal-bearing, and marine strata occur. Not only are these strata as a rule thicker, but also they are more generally of marine origin, than the Pennsylvanian strata of the Appalachian region.

In the Rocky Mountains and westward in the United States, the Pennsylvanian rocks are practically all of true marine character and consist largely of limestone and shale with some sandstone and little coal, thus being in marked contrast with the rocks of the system in eastern North America (Fig. 253).

In the Appalachian district, the system ranges in thickness from about 1500 feet to approximately 10,000 feet. A maximum thickness of 13,000 feet is known in Nova Scotia and 12,000 feet in Rhode Island. Through the Mississippi Basin the thickness is usually not more than

FIG. 251. Pennsylvania strata with a coal bed (black layer) 18 inches thick. About 15 miles southeast of Uniontown, Pennsylvania.

1000 to 2000 feet, though in Arkansas a thickness of over 15,000 feet has been found. In the western United States the thickness varies much, though it is usually at least several thousand feet. The nearly complete system in central Texas is over 5000 feet thick.

Plutonic rocks definitely known to be of Pennsylvanian age are practically absent from North America. On the Pacific Coast from northern California to Alaska, volcanic rocks—both lavas and tuffs—are directly associated with altered Pennsylvanian strata.

Notably metamorphosed Pennsylvanian strata (e.g. *Roxbury* conglomerate) occur in southeastern New England and locally in the mountains of the west.

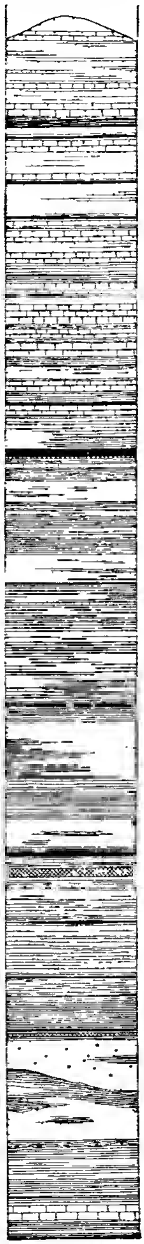
| System | Kind of Rock | Columnar section | Thickness in feet |
|---|---|---|---|
| Permian | *Dunkard* sandstone, limestone and coal |  | 300± |
| Pennsylvanian | *Monongahela* shale, sandstone, limestone and coal | | 310 to 400 |
| | *Conemaugh* shale, sandstone and little coal | | 600 |
| | *Allegheny* shale, sandstone and coal | | 280 |
| | *Pottsville* sandstone and some coal | | 150 |
| Mississippian | *Mauch Chunk* shale, sandstone and limestone | | 150 |

FIG. 252. Geologic (columnar) section in western Pennsylvania showing the vertical distribution of coal beds (heavy black bands) and their relations to associated strata. (After Campbell, U. S. Geological Survey, Folio 94.)

**Pennsylvanian History.** *The Seas.* Disregarding relatively minor oscillations of level between land and sea, the outstanding feature in regard to the relations of land and water during Pennsylvanian time was progressive submergence of a considerable portion of the continent, beginning in the east and spreading westward and then northwestward to Alaska.

As we learned in the preceding chapter, the Mississippian period closed with a widespread emergence of all the submerged areas in eastern North America. Very early in the Pennsylvanian the sea began to transgress over the land by extending a long, narrow estuary north-

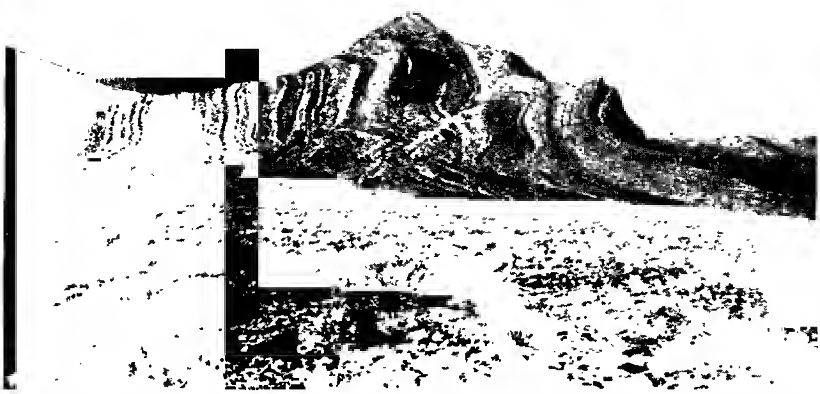


FIG. 253. A mountain of Pennsylvanian (?) marine limestone. The nearly vertical beds show a thickness of fully 2000 feet. Southern part of Panamint Mountains, California.

ward through the Appalachian district as far as Pennsylvania. Gradually the sea expanded and extended over much of the interior region now containing Pennsylvanian coal, through central Texas, and westward across northern Mexico to the Pacific Ocean. There was probably a narrow eastern connection with the Gulf of Mexico. The marine waters, particularly in the east, were often intermittent with low swampy lands with conditions favorable for growth and accumulation of plant material later to become coal.

In the Gulf of St. Lawrence and southeastern New England areas, non-marine deposition of both sediments and plant materials occurred.

The relations of land and sea much as just described continued into

early Middle Pennsylvanian time, and the sea gradually expanded to the late Middle of the period (early Conemaugh time). This was the greatest Pennsylvanian sea and it covered fully one-third of the continent (Fig. 254). The vast sea swept from the Appalachian Mountains

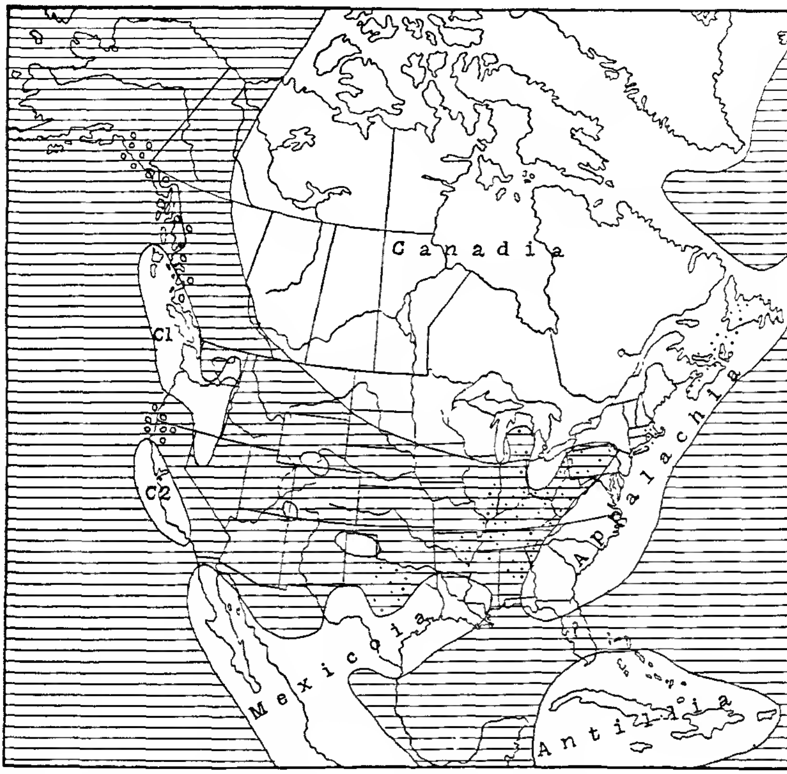



FIG. 254. Generalized paleogeographic map showing the sea and land areas in North America during Middle Pennsylvanian time. White areas, land; ruled areas, sea. C1, C2 are parts of Cascadia. The dotted areas show alternating sea and land conditions in the Appalachian-Interior Lowland region, and non-marine depositional conditions in the southeastern New England and Gulf of St. Lawrence regions. Coal-producing plants thrived in these areas. Small circles show volcanic areas on the Pacific Coast. Principal data (modified) from maps by B. Willis, J. Weller, and C. Schuchert.

westward over the area of most of the United States, and northward over the Rocky Mountain region of western Canada and all (or nearly all) of Alaska. Volcanoes then were active in northwestern California, western British Columbia, and southern Alaska. No sea has ever again

spread over the area of the United States from the Appalachian region to the Pacific Ocean.

The latter part of the period was marked by a great restriction of the sea as shown by Figure 255. All that remained of the western sea was a large embayment across northern California and into Utah and

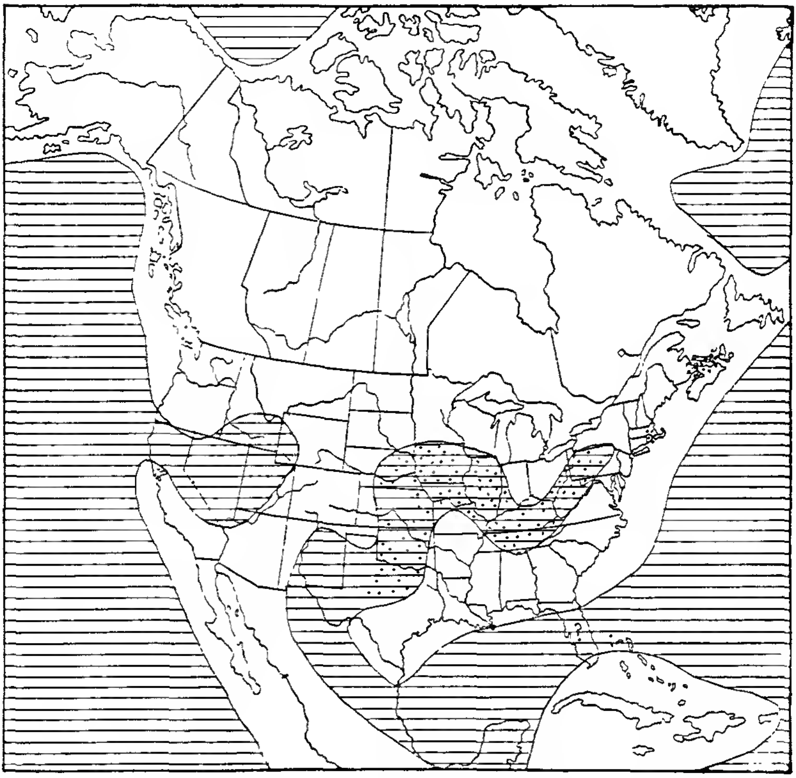


FIG. 255. Generalized paleogeographic map showing sea and land areas in North America during Late Pennsylvanian time. White areas, land; ruled areas, sea; dotted areas, as in Figure 254. Principal data (modified) from maps by C. Schuchert.

western Wyoming. In the eastern United States marine, estuarine, lacustrine, and marsh and bog conditions alternated in most of the basin of deposition, and there were prolific and extensive growths of coal-producing plants.

In Nova Scotia non-marine sediments and vegetable materials were deposited.

*Origin of the Coal Beds.* Since the remarkable physical geography conditions of Pennsylvanian time favored the accumulation of the world's greatest coal beds, they deserve more detailed discussion. "Perhaps the most perfect resemblance to coal-forming condition is that now found on such coastal plains as that of southern Florida and the Dismal Swamp of Virginia and North Carolina. Both of these areas are very level, though with slight depressions in which there is either standing water or swamp condition. In both regions there is such general interference with free drainage that there are extensive areas of swamp, and in both there are beds of vegetable accumulations. In each of these areas there is a general absence of sediment and therefore a marked variety of vegetable deposit. If either of these areas were submerged beneath the sea, the vegetable remains would be buried and a further step made toward the formation of a coal bed. Reëlevation, making a coastal plain, would permit the accumulation of another coal bed above the first, and this process might be continued again and again" (H. Ries: *Economic Geology*, 1910, p. 9). It is, however, not necessary to assume repeated elevation and subsidence of swamp areas in order to account for numerous coal beds one above another in a given region. A general subsidence, often intermittent (with possibly some upward movements), would occasionally cause the luxuriant vegetation of a great swamp area to be killed and allow the deposition of sediment over the site. Then the filling of the shallow water with sediment would allow another bog to be formed, etc. In the coal field of Nova Scotia there are 76 distinct coal beds; in Alabama 35; in Pennsylvania at least 20; and in Illinois 9. Each of these coal beds represents an ancient swamp in which grew a luxuriant vegetation. It should be borne in mind that workable coal seams constitute only about 2 per cent of the containing strata which are sandstones, shales, clays, and, in some localities, limestones.

Perhaps no single coal seam in the world underlies such a large area (12,000 to 15,000 square miles) as the famous Pittsburgh coal bed. It is worked over an area of about 6000 square miles, and for 2000 square miles it averages 7 feet in thickness. Most of the swamps or bogs of Pennsylvanian time were much smaller than this.

In the anthracite coal district of eastern Pennsylvania, the famous "Mammoth" coal bed is remarkable for its great thickness up to 50 or more feet.

*Ouachita Revolution.* Mention has already been made of the so-called Ouachita Disturbance toward the close of the Mississippian period when the Ouachita Mountain region of Arkansas and Oklahoma was

somewhat folded and elevated. According to H. D. Miser, however, "the 25,000 feet of exposed strata of Paleozoic age in the Ouachita Mountains were subjected to great compressive movements during the middle or later part of the Pennsylvanian." The strata were then highly deformed, often with development of overturned folds and thrust faults, as shown in the accompanying structure section (Fig. 256).

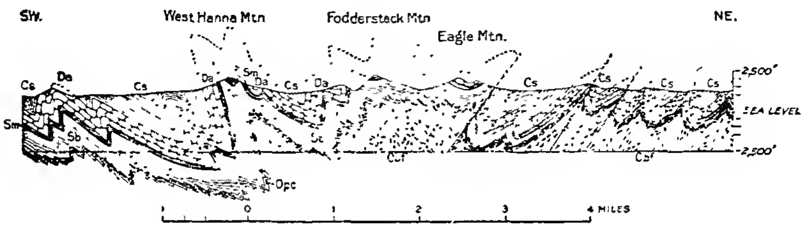



FIG. 256. Structure section through part of the southern Ouachita Mountains, near Shady, Arkansas. *Obf, Opc* = Ordovician; *Sb, Sm* = Silurian; *Da* = Devonian; and *Cs* = Late Mississippian. (After Miser and Purdue, U. S. Geological Survey.)

This was the real *Ouachita Revolution*, resulting in a mountain range with an east-west trend.

The so-called Ancestral Rockies extended from northern New Mexico through Colorado into southern Wyoming.

**Pennsylvanian Climate.** Many years ago the plant life of the great coal period was thought to imply a warm to tropical, very moist, uniform climate. More careful study, however, clearly points to a temperate, only relatively humid, but remarkably uniform climate. Some of the criteria favoring this latter view may be stated as follows: The great size and height of the plants together with their frequent succulent nature and spongy leaves indicate luxuriant growth in a moist, mild climate; absence of annual rings of growth shows absence of distinct change of seasons; the presence of aërial roots, by analogy with similar modern plants, implies a moist and warm climate; the nearest present-day allies of the coal plants attain greatest growth in warm and humid climates; at present the greatest accumulations of vegetable matter in bogs and marshes take place in temperate climates where decay is not too rapid and thus suggests a similar climate for the accumulation of the coal deposits; and the remarkable distribution of almost identical plant types in Pennsylvanian rocks from Arctic to tropical regions clearly shows a pronounced uniformity of climate over the earth.

## Permian Period

**Permian Rocks.** Compared with the preceding Paleozoic systems, Permian strata occur almost entirely in the western one-half of North America (Fig. 257). Permian plutonic rocks are, however, abundantly represented on the Atlantic Coast from Newfoundland to Alabama (Fig. 291).

In the western United States the Permian strata are considerably more extensive than their surface distribution because they are concealed under Mesozoic or Cenozoic rocks over large areas. Also there is some reason to think that the Permian strata formerly extended over much of the Great Basin region, but have been removed by erosion, leaving much Pennsylvanian or Mississippian rock now at the surface. In the eastern United States, however, the few small areas shown on the map (Fig. 257) comprise all of the Permian except possibly some

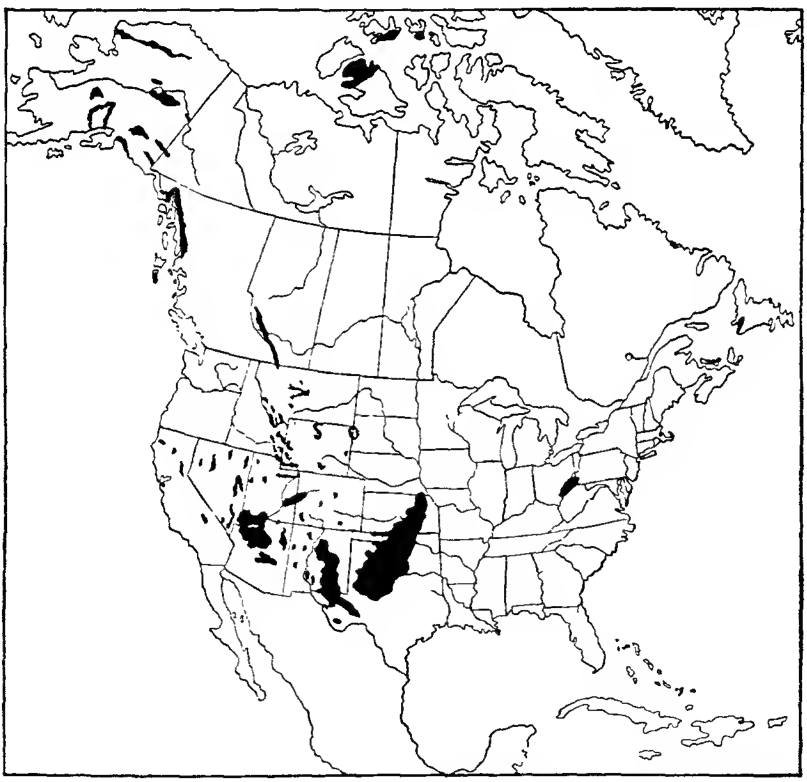


FIG. 257. Map showing known areas of outcrops (surface distribution) of Permian strata in North America.

in the lower Mississippi Valley where Mesozoic and later rocks effectually conceal the older rocks.

The Permian strata in the small area of the northern Appalachian district are in every way much like the Pennsylvanian just below.

In Kansas the Permian rocks are divisible into two rather distinct series, the lower series of shales and limestones being largely marine, while the upper series of sandstones, shales, limestones, salt, and gypsum are mostly not truly marine and they are characterized by a prevailing red color.

The central Texas Permian strata are chiefly "Red Beds" of mostly non-marine origin, including sandstones, limestones, red and blue shales, and some salt and gypsum beds.

Western Texas and southeastern New Mexico contain what is probably the most complete set of Permian strata known in North America. The section shows fully 7000 feet of marine strata, largely limestones and shales.

The Middle Permian salt beds of Kansas, Oklahoma, and Texas underlie an area of fully 100,000 square miles, reaching a total thickness of more than 1000 feet in Texas.

Strata, mostly of non-marine origin and containing much red materials like those of central Texas and Kansas, are also found through New Mexico, western Colorado, and Wyoming.

In the states farther west, including Arizona, Utah, Idaho, Nevada, and California, there are both marine and non-marine formations of Permian age. Four formations—*Supai* red sandstone and shale, *Hermit* red shale, *Coconino* gray sandstone, and *Kaibab* white limestone (at the top)—constitute the upper 2000 feet of the picturesque walls of the Grand Canyon of Arizona. The Kaibab is of marine origin, but the others are largely or wholly non-marine.

In the Gulf of St. Lawrence region the Permian consists mostly of "Red Beds," including conglomerates, sandstones, and shales.

In Pennsylvania and Ohio the Dunkard series (Lower Permian only) shows a thickness of about 1000 feet. A thickness of 2000 feet for the whole system is reported from Kansas; 5000 to 7000 feet in Texas; 3800 feet in Utah; 2000 feet in the Grand Canyon; 6000 feet in Alaska; and 9000 feet in the Gulf of St. Lawrence region.

Plutonic igneous rocks (mainly granites) of Permian, and possibly somewhat earlier, age occur in numerous large and small bodies in the Piedmont Plateau and so-called older Appalachians, especially in their

southern portions, and also in New England, New Brunswick, Nova Scotia, and Newfoundland (Fig. 291).

Diorites, probably of Permian age, occur in the Sierra Nevada.

Volcanic rocks occur in the Permian system in parts of northern California and southern Alaska.

Permian strata in the western mountains are in places moderately metamorphosed.

**Permian History.** *The Seas.* Early in Permian time an interior sea spread over much of Nebraska, Kansas, western Oklahoma, central

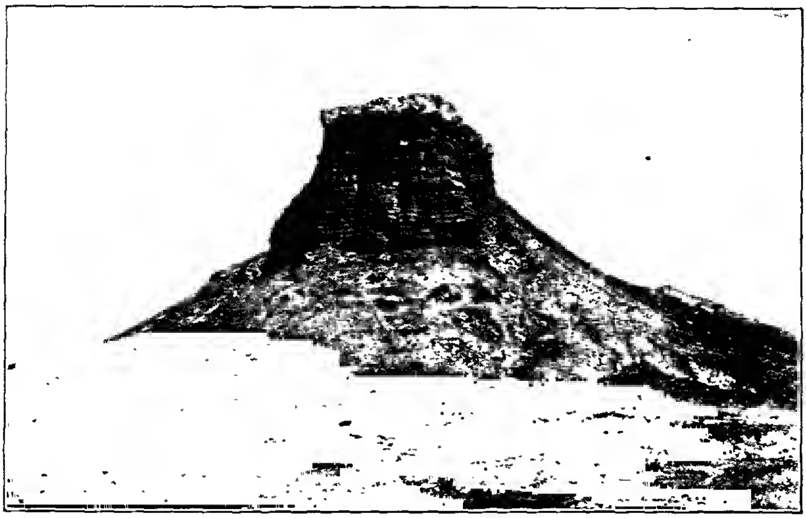


FIG. 258. Late Permian or early Triassic "Red Beds" in Red Butte, eastern Wyoming. The bright red strata are capped by a 30-foot layer of white gypsum. (After Darton, U. S. Geological Survey, Folio 127.)

and western Texas, New Mexico, and eastern Colorado and Arizona. This sea seems to have been connected with the Gulf of Mexico through eastern Mexico. At the same time northern California and much of Alaska were submerged. The Early Permian strata (including coal) in the northern Appalachian district clearly prove a continuation of the Coal Measures conditions, that is, large fresh-water swamps or basins and prolific plant growth.

By Middle Permian time the western sea became much enlarged and connected with the Pacific Ocean through northern California and through western Canada, at the same time covering all (or nearly all)

of Alaska. This was the greatest Permian sea. Figure 259 shows the sea and land relations of that time.

Rising out of the Middle Permian southwestern sea, a bold range, called the Ancestral Rockies, extended from central Wyoming into northeastern New Mexico. A more or less cutoff arm of the sea or


FIG. 259. Generalized paleogeographic map showing sea and land areas in North America during Middle Permian time. This was the greatest Permian sea. White areas, land; ruled areas, sea. *A*, Ancestral Rockies. Small circles show volcanoes on the Pacific Coast. Principal data (modified) from maps by C. Schuchert and R. Kirkham.

basin lay just east of this range during much of Middle Permian time. According to R. A. Jones, a great coral reef, now clearly traceable in fossil form across westernmost Texas and southeastern New Mexico, existed as a barrier separating this lagoonal basin from the sea on the west. In this basin, lying in an arid region, conditions were favorable

for the deposition of the so-called "Red Beds" and associated great beds of salt and gypsum.

In the Gulf of St. Lawrence region, Permian strata are also chiefly of continental origin, suggesting conditions of deposition similar to those in Texas and Kansas, except that salt and gypsum are practically absent.

A glacial deposit of Permian age in eastern Massachusetts shows that conditions were favorable for at least local glaciation there. Permian deposits of more doubtful glacial origin have been reported from Prince Edward Island (in Gulf of St. Lawrence) and from parts of Alaska.

Middle Permian volcanoes were active in northwestern California and southern Alaska.

In Late Permian time the great western sea almost completely vanished, leaving only western Texas, southern New Mexico, and eastern Mexico submerged. This was the last remnant of the wonderful succession of the numerous North American Paleozoic epeiric seas. Late Permian volcanoes were active in northern California and southern Alaska.

At the close of the Permian the sea completely disappeared from the continent.

*Close of the Permian (Appalachian Revolution).* The Paleozoic era was brought to a close by one of the most profound physical disturbances in the history of North America. It has been called the Appalachian Revolution because at that time the Appalachian Mountain Range was born out of the sea by upheaval and folding of the strata. Perhaps it would be better to say that the revolution reached its climax at about the close of the Paleozoic because the evidence is clear that the upward movement began at least as early as the Pennsylvanian, and slowly increased to the close of the era. Since Permian strata are involved in the folding along the western side of the Appalachians, we know that much of the disturbance must have occurred after the deposition of those strata.

All through the vast time (many millions of years) of the Paleozoic era, a great land-mass (Appalachia) existed along what is now the eastern coast of the United States. Its western boundary was, most of the time, just east of the present Appalachians, while it must have extended eastward at least as far as the border of the continental shelf. Concerning the altitude and the character of the topography of Appalachia we know almost nothing, but we do know that it consisted of

rock of pre-Cambrian age. The enormous amount of sediment derived from it shows that Appalachia was high enough during nearly all of its history to undergo vigorous erosion. Although oscillations of level more than likely affected the land-mass, and its western shore line was quite certainly shifted at various times, nevertheless it persisted as a great land area with approximately the same position during all of its long history. Its general position is well shown on the various Paleozoic paleogeographic maps.

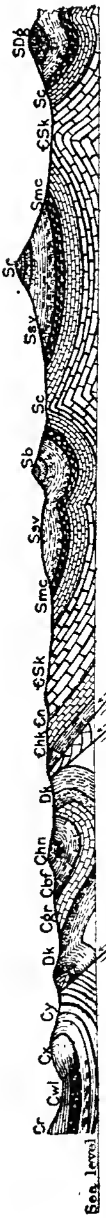



FIG. 260. Structure section through a portion of the Appalachian Mountains of western Virginia showing the typical deformation of Paleozoic strata. Length of section, 12 miles. *Chk* and *Cn* = Cambrian; *Csk* = Cambro-Ordovician; *Sc, Smc, Ssv, Sb* = Ordovician; *Sr* = Silurian; *SDg* = Siluro-Devonian; *Dk* = Devonian; and *Cqr, Cbf, Cy, Chn, Cx, Cwl, Cr* = Mississippian and Pennsylvanian. (After Campbell, U. S. Geological Survey, Folio 44.)

Barring certain minor oscillations of level, all of the region just west of Appalachia was occupied by sea water during much of the Paleozoic era, and sediments derived from the erosion of Appalachia were laid down layer upon layer upon that sea bottom. The coarsest and greatest thickness of sediments deposited nearest the land, that is, along what we might call the marginal sea bottom. At the same time, finer sediments and limestones in thinner sheets were being deposited over much of the Mississippi Valley region. By actual measurement, in the present Appalachians, we know that the maximum thickness of these sediments was at least 35,000 feet. Now, since these are all of comparatively shallow water origin, as proved by the coarseness of sediments, ripple marks, fossil coral reefs, etc., we are forced to conclude that this marginal sea bottom gradually sank during the process of sedimentation, thus producing what is called a great geosynclinal trough. Perhaps the very weight of accumulating sediments caused this sinking. Finally, toward the close of the Paleozoic era, sinking of the marginal sea bottom and deposition of sediments ceased, and a tremendous force of lateral compression was brought to bear, causing the strata to become highly folded and more or less faulted. Thus arose the great Appalachian Mountain range which, in its prime, was doubtless much loftier than it is today.

This tremendous deformation took place very slowly, though during a short time as compared with the length of the Paleozoic era. As soon as the folds appeared well above sea-level, irregularities began to be carved out by the work of erosion so that even from early youth the mountains presented a rugged surface. Mountains now in process of growth, like the Coast Ranges of California, show such ruggedness. The great thrust faults, especially of the southern and central Appalachians, where certain blocks of the earth's outer shell have been pushed for miles to the northwest over others, were not produced by single movements, but rather by many repeated movements along single fault surfaces. Some of these faults are hundreds of miles long.

Important orogenic movements through New England and into the Gulf of St. Lawrence region took place at the same time. Great thrust faulting occurred in western New England. Accordingly, the whole eastern border region of the continent, for a distance of 2000 miles, was profoundly affected by mountain-making disturbances.

The Appalachian Revolution was accompanied by tremendous intrusions of granite magma throughout New England, New Brunswick, and Newfoundland, and to the east of the Appalachian Mountains proper, particularly in the Piedmont Plateau and the so-called "Older Appalachians." The granite is now widely exposed in these regions. An important factor contributing to the present-day height and ruggedness of northern New England and of the southeastern "Older Appalachian" region is the outcropping of so much of this resistant granite. The two regions last mentioned are the highest and most rugged in eastern North America, the highest peak of all being Mt. Mitchell in North Carolina with an altitude of 6684 feet.

It should be clearly understood that the original Appalachian Mountains were greatly worn down and then rejuvenated to form the present-day mountains.

Other important geographic changes in addition to the above were (1) the warping of the surface of Appalachia as we shall show in our discussion of the Triassic period; (2) the uplift of the Mississippi Basin, with little deformation of the strata, east of the Great Plains never again to become submerged to the present time except along the Gulf Coast; (3) the elevation and erosion of many of the Permian areas west of the Rocky Mountains in the United States, which thus accounts for a rather widespread unconformity between the Permian and Triassic in those areas; and (4) considerable deformation of the rocks, accompanied by metamorphism of strata and intrusion of plutonic bodies (mainly diorites), in the Sierra Nevada region.

All of North America was a land area, much of it high above sea level, at the end of Permian time.

**Permian Climate.** During Permian time there was a remarkable combination of climatic conditions, including extensive glaciation especially in the southern hemisphere (at low latitudes), widespread aridity in parts of North America and Europe, and conditions favorable for prolific growth of coal-forming plants in various parts of the world, all in a single period. Thus the climate of the Permian presented a striking contrast to the mild and rather uniform climate of the immediately preceding period. The concentration of the extensive glaciation over low-latitude, instead of high-latitude, regions is difficult to account for.

These perplexing problems may be in part explained as follows. The profound mountain-making disturbances, resulting in so many great and small uplifts in so many large parts of the world, caused (1) general disappearance of seas from continents and great interference with the free play of ocean currents, thus much reducing the temperature equalizing influence of the seas: (2) low temperatures over extensive regions newly raised to high altitudes, even in low latitudes; and (3) heavy precipitation on the windward sides of new mountain ranges which rose across the paths of prevailing winds, and low precipitation on the opposite sides.

## Structures of the Paleozoic Rocks

Paleozoic strata occurring in the Appalachian Mountains, New England, Gulf of St. Lawrence region, Ouachita Mountains, Rocky Mountains, and other mountains of western North America (including Alaska) are usually more or less strongly folded and often faulted. Both normal and thrust faults affect the strata, some of the thrusts being of great magnitude, as in the southern Appalachians, western New England, the Rocky Mountains, and southern Nevada.

In other large regions, such as the Interior Lowland, the Appalachian Plateau, the Great Plains (mostly concealed), southwest of Hudson Bay, and the Mackenzie River Basin, the Paleozoic strata have been but little disturbed from their original horizontal position.

Batholithic structures resulted from large and small intrusions of Paleozoic magma, particularly toward the end of the era in the eastern highland region extending from Alabama to Newfoundland (Fig. 291).

# CHAPTER XX

## PALEOZOIC LIFE

### Plants

In order to gain even an elementary knowledge of the history and evolution of plants, the reader should bear in mind the important fact that plants of higher, more complex types came into existence during geological time in almost exactly their general botanical order of classification. In other words, from the primitive, single-celled plants of Archeozoic and Proterozoic times, there have evolved more complex forms culminating in the highly organized plants of today.

A simple classification involving some of the main divisions of plants is here given:

- I. Seedless Plants . .
  - 1. Thallophytes (e.g. algæ and fungi).
  - 2. Bryophytes (e.g. mosses and liverworts).
  - 3. Pteridophytes
    - 1. Filicales (e.g. ferns).
    - 2. Arthrophytes (e.g. horsetail rushes).
    - 3. Lepidophytes (e.g. club mosses).
- II. Seed Plants (Spermatophytes) . . . .
  - 1. Gymnosperms (Flowerless)
    - 1. Pteridosperms (" seed ferns ").
    - 2. Cordaites.
    - 3. Cycads (e.g. " sago palms ").
    - 4. Conifers (e.g. pines, spruces, and sequoias).
  - 2. Angiosperms (Flowering)
    - 1. Monocotyledons (e.g. grasses, grains, palms, and lilies).
    - 2. Dicotyledons (e.g. most hardwood trees, bushes, herbs, and familiar open-flowering plants).

There are certain rather obscure impressions and cluster-like forms in Cambrian rocks which may be seaweeds, but their identification is often unsatisfactory. In the earlier Paleozoic periods simple plants at least must have been abundant since animals ultimately depend upon plants for food. Their scarcity as fossils is doubtless due to the unfavorable nature of the simple (soft) marine plants for fossilization.

Recently certain problematical Cambrian fossils, long known by the name "Cryptozoön," have been determined as algae by Walcott. They secreted concentric layers of carbonate of lime and lived in water. In

some localities, as near Saratoga Springs, New York, distinct beds or "reefs" of such algæ occur, in limestone.

There is no evidence that any types of plants other than single-celled water-dwelling forms existed during Cambrian time. This is a remarkable fact not only in view of the tremendous lapse of Archeozoic and Proterozoic time, but also of the profound post-Cambrian evolution in the plant world.

Various kinds of seaweeds (marine algae) are definitely known from Ordovician limestones and shales, and also from Silurian sandstones.

Definite knowledge of Ordovician land plants is very scant, making the following recent (1935) discovery especially significant. According to Science Service "fossils of fernlike plants of very simple structure, with a great deal of branching stem, but with nothing that can be surely identified as leaves, have been found in a deposit of Lower Ordovician limestone in Wyoming by E. Dorf. Together with similar fossils found in a very few scattered places over the earth, they belong to the oldest known groups of land plants known as Psilophytales."

Our knowledge of Silurian land plants is also very meager. Some mosslike and fernlike forms of doubtful affinities have been reported. In regard to certain fragments of plants found in Silurian strata in England, Sweden, and Australia, Seward says that "they afford evidence of the existence of two Silurian types, probably terrestrial, which agree closely with forms characteristic of the earlier Devonian floras, and of a third type that appears to be peculiar to this meager pre-Devonian flora." Considering the profuse land vegetation of the next (Devonian) period, it seems certain that their progenitors must have been well represented in the Silurian, and that either more of their remains will be discovered, or that the conditions for their preservation were unfavorable.

Devonian lands were covered with a rich and diversified vegetation, often even with luxuriant forests. The forests were, however, far different in appearance from those of the present because the trees were all of very simple or low organization types. Fig. 261 represents one of these very primitive trees. Thus they were largely represented by all the main subdivisions of the seedless plants and primitive types of low-order gymnosperms. Because these important and remarkable land plants reached their climax of development in the Pennsylvanian (great coal period), it will serve our purpose best to discuss these plants in connection with the flora of that period.

During Mississippian time there were comparatively few important evolutionary advances in the plant world.

The plant life of Pennsylvanian time was very prolific and the records for this period are far more abundant than for any other paleozoic period, one reason for this unusually full record doubtless being the

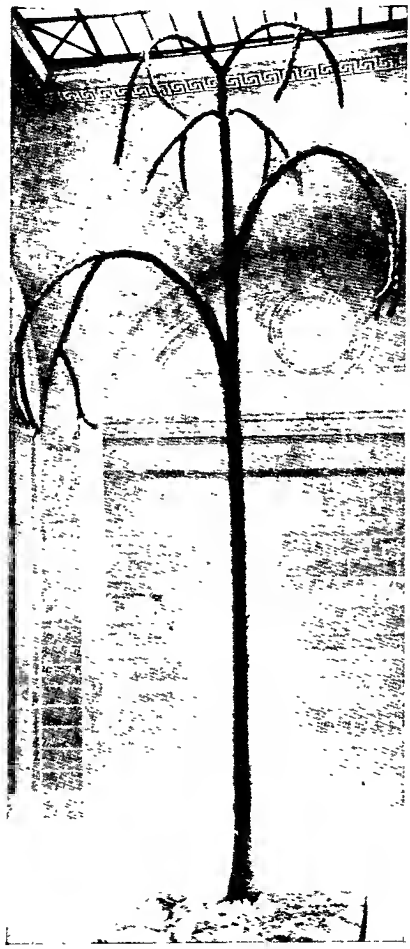


FIG. 261. A restoration of one of the oldest trees of the earth. It is a primitive lepidophyte (*Archeosigillaria primeva*) reconstructed from a specimen found in the Devonian strata of New York. (Courtesy of the New York State Museum.)

very favorable conditions for preservation of the flora of the time. Several thousand species of now extinct plants are known from the Pennsylvanian alone. It must be remembered that most of the important classes of Pennsylvanian plants existed as early as in the Devonian,

but these earlier records are much more scant. The known Pennsylvanian flora consists almost entirely of pteridophytes and the lower forms of gymnosperms, though thallophytes (e.g. algæ) certainly, and bryophytes probably, also existed. From the negative standpoint, the most significant feature was the complete absence of the typical flowering

Fig. 262. A late Paleozoic landscape, showing some of the most conspicuous plants of the great Coal Age. Lepidodendrons (with branches) and sigillarians (without branches) in the left background; arthrophytes (segmented) on the right; seed ferns in the left foreground; two amphibians (*Eryops*) on the land; a primitive reptile (*Limnoscelis*) in the water; and a great insect (dragon fly) in the air. (From a drawing by Prof. S. W. Williston.)

plants (angiosperms) which are today the most common and the most advanced of all plants.

*Filicales* (true ferns) were fairly common and diversified, both as treelike forms and as small, herbaceous forms. Both forms were very similar in appearance to those now living in tropical and temperate climates.

*Arthrophytes* ("horsetail" rushes) were also common in the Pennsylvanian forests. These plants had long, slender, segmented stems which were either hollow or filled with a large, soft pith. The leaves, which were arranged in whorls around the stems at the joints, were of variable

shapes and sizes, usually either needlelike, scalelike, or straplike. The outside of the stem had a sort of finely fluted structure but without scars and not continuous as in the sigillarians. They reached heights of 60 to 90 feet and diameters of 1 or 2 feet (Fig. 262). Arthrophytes are today chiefly represented by only a few species of rushlike forms not

FIG. 263. A fossil lepidophyte (sigillarian) stump in the Pennsylvanian strata of Nova Scotia standing in the position where the tree grew. (Courtesy of the Geological Survey of Canada.)

over a few feet high, though in South America some very slender forms grow to heights of 30 to 40 feet.

*Lepidophytes* (giant "club-mosses") were the largest, most abundant, and conspicuous of the forest trees of the Pennsylvanian, and they appear to have culminated during this same period. In marked contrast to such a high position, their descendants of today are represented only by a few, small, delicate, trailing so-called "club-mosses" and "ground

pines" in our forests. Two of the most prominent of the Pennsylvanian lepidophytes were the lepidodendrons and the sigillarians. The lepidodendrons ("scale-trees") had leaf-scars or scales arranged spirally around the trunks of the trees. They generally attained a height of 50 to 100 feet and a diameter of 2 to 4 feet (Fig. 262). The tall trunks were slender and they branched dichotomously (by twos) only at a considerable height. Long, stiff, needle-shaped leaves were thickly set on the branches. The dropping of the leaves from the older (trunk) portions caused the leaf-scars or scales above mentioned. Inside of the outer bark, the stem consisted of pithy or loose cellular tissue. Over 100 species of the lepidodendron are known. The sigillarians ("seal-trees") are so called because of the seallike markings which were arranged vertically on the tree trunk. They were even larger than the lepidodendrons, having attained a height of 100 feet or more and a diameter of 5 to 6 feet (Fig. 262). The trunk seldom branched and it ended with a rounded tip. In other respects these trees were much like the lepidodendrons.

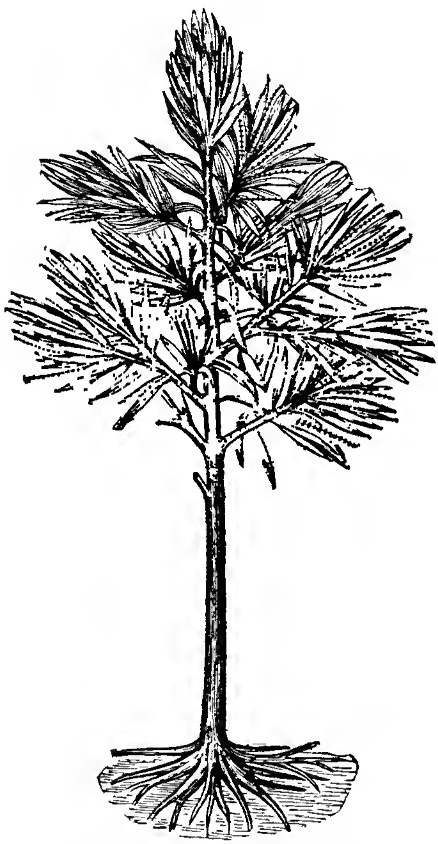


FIG. 264. Cordaites restored. (From Schuchert's "Historical Geology," courtesy of John Wiley and Sons.)

*Pteridosperms* ("seed ferns"), which were common in the Pennsylvanian, comprised a remarkable group of plants recently regarded as transitional between the seedless and seed plants. They possessed seeds but not flowers and showed many features which seem to make them the connecting link between the ferns and the cycads. The seeds were arranged on the leaves. There is a considerable

difference of opinion concerning the relations and affinities of this remarkable group of plants, now long extinct.

*Cordaites* were common representatives of low-order gymnosperms. They were comparatively slender trees which attained a diameter of 2 or 3 feet and a height of 90 feet or more (see Fig. 264). The branches, which were given off only toward the top of the trunk, were supplied with numerous, long, very simple, parallel-veined, strap-shaped leaves notable for great size, sometimes 5 or 6 feet long and 5 or 6 inches wide. The trunks were covered with thick bark, while inside there was much pith. Many specimens have been well preserved. They were important contributors to the formation of some coal beds. They possessed certain features or structures of the seed ferns, conifers, cycads, and ginkgos in addition to their own characteristics. Cordaites thus afford a fine illustration of a generalized type of plant, that is to say one which combined the characters of several distinct (some later) forms.

In Permian time the most important advances in the plant world occurred among the *gymnosperms*. In addition to the *cordaites,* which continued from the Pennsylvania, *cycads* and *conifers* are known for the first time, thus giving the flora a decided Mesozoic aspect. The introduction of the cycads and conifers marked a distinct advance in the plant world, the cycads having evolved from the seed ferns, and the conifers from cordaites. Ginkgo ("maidenhair") trees also evolved from cordaites or an allied plant during the Permian.

## Animals

Some knowledge of the classification and main characteristics of the more important groups of animals is a fundamental consideration in the study of the life of the past ages of geologic time, particularly in its bearing upon the great doctrine of organic evolution. The following simple classification includes various important subdivisions of animals, most of which are often represented in fossil form. Reading downward in this table, there is a gradually increasing complexity of structure, ranging from single-celled forms to the most highly organized animals which ever lived. Just as it is true of the history and evolution of plants, so here it is a remarkable fact that animals have evolved, or become more and more complex, as geologic time has gone on.

| | | |
|---|---|---|
| I. | Protozoans, e.g. foraminifers | |
| II. | Sponges | |
| III. | Cœlenterates | 1. "Jellyfishes" and graptolites.<br>2. Corals. |
| IV. | Echinoderms | 1. Stalked forms—e.g. "stone lilies."<br>2. "Starfishes"<br>3. "Sea urchins." |
| V. | Worms | |
| VI. | Molluscoids | 1. Bryozoans—e.g. "sea mosses."<br>2. Brachiopods. |
| VII. | Mollusks | 1. Pelecypods—e.g. clams, oysters.<br>2. Gastropods—e.g. snails.<br>3. Cephalopods—e.g. nautilus, "cuttlefishes." |
| VIII. | Arthropods | 1. Crustaceans—e.g. crabs, trilobites.<br>2. Arachnids—e.g. spiders, eurypterids.<br>3. Insects. |
| IX. | Vertebrates | 1. Simplest vertebrates—e.g. ostracoderms.<br>2. Fishes.<br>3. Amphibians—e.g. frogs, salamanders.<br>4. Reptiles.<br>5. Birds.<br>6. Mammals (including man). |

Many thousands of species of fossil animals are known from Paleozoic strata. Even the earliest (Cambrian) period of the Paleozoic era is represented by an abundant and varied assemblage of fossil animals in marked contrast to the meager fossil record of pre-Paleozoic times. Many of the sub-kingdoms of animals were represented though usually only by simpler or more primitive types in each sub-kingdom, the higher types having evolved in subsequent times. The great contrast in the fossil records of Cambrian and pre-Cambrian times is probably in no small measure due to the fact that nearly all pre-Cambrian animals lacked shells or hard parts favorable for preservation as fossils.

*Protozoans,* which are single-celled animals, have left a fossil record ranging through Paleozoic time. Perhaps the best known of these tiny creatures were the foraminifers which secreted shells of lime carbonate (Fig. 301). Such creatures now swarm in large portions of the surface sea waters. It is a remarkable fact that such exceedingly simple and primitive types of creatures have persisted through countless ages of geologic time while tremendous evolutionary changes have brought the animal world to the high plane represented by man.

*Sponges* represent the simplest of the many celled animals. They are porous, saclike forms. They ranged throughout Paleozoic time, and even to the present day, with no outstanding evolutionary change.

*Cœlenterates* are also saclike forms, but they have tentacles around a distinct mouth opening. Among these the so-called "jellyfishes" are soft gelatinous forms known to have left fossil casts even in Cambrian

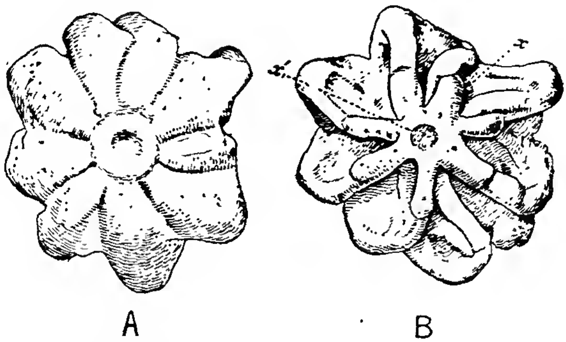



FIG. 265. A Cambrian jellyfish, *Brooksella alternata*. *A*, top; *B*, bottom. (After Walcott, from Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

strata. The *graptolites* lived only during early and middle Paleozoic time. They were slender, plume-like, delicate forms consisting of colonies of tiny individuals (Fig. 266). Because they were numerous,

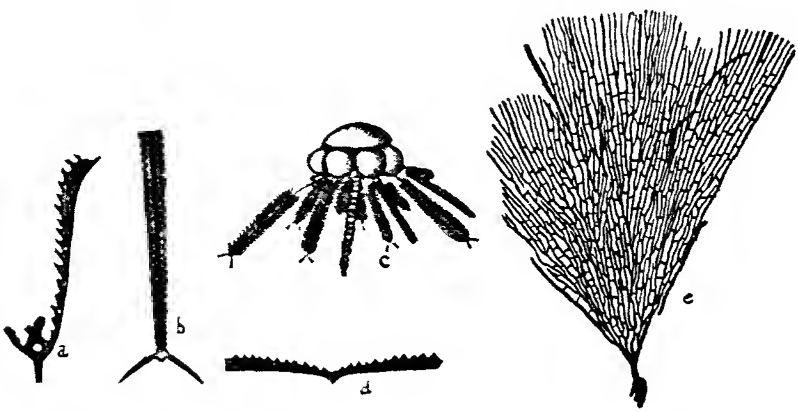
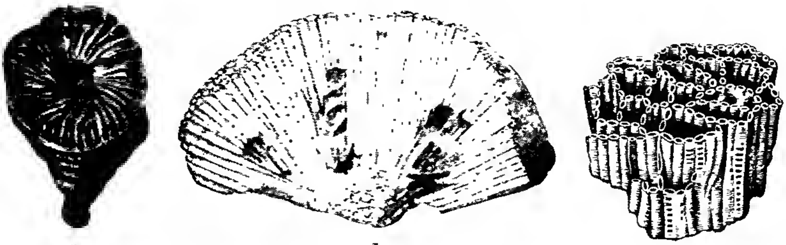



FIG. 266. Ordovician graptolites: *a*, *Tetragraptus fructicosus*; *b*, *Climacograptus bicornis*; *c*, *Diplograptus pristis*; *d*, *Didymograptus nitidus*; *e*, *Dictyonema flabelliforme*. (*a*, *b*, *d*, after Hall; *c*, after Ruedemann; *e*, after Matthew.)

changed species often, and floated in the open sea (hence widespread), their fossil forms are very valuable for correlating and determining the geologic ages of earlier and middle Paleozoic strata.

*Corals* are still higher forms of cœlenterates, having evolved from sponges in early Paleozoic time. They were common throughout the Paleozoic era, their carbonate of lime skeletons often having accumulated



*a* *b* *c*

Fig. 267. Silurian and Devonian corals: *a*, Cup coral, *Zaphrentis roemeri* (M. Edwards and Haime) (Devonian form); *b*, Honeycomb coral, *Heliolites pyriformis* (Guettard); *c*, Chain coral, *Halysites catenulatus* (Linn.).

to help build up great and extensive deposits of limestone. Paleozoic corals were simpler and notably different from modern corals, which made their first appearance in Permian time. The partitions are six o

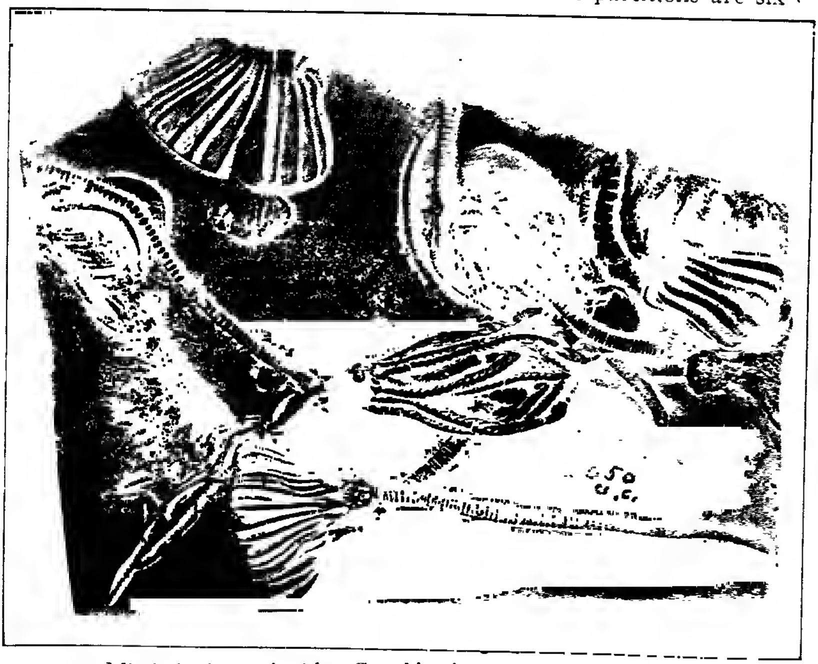


Fig. 268. Mississippian crinoids, *Graphiocrinus longicirrifer* and *Rhodocrinus Kirbyi*, on a slab of limestone. Considerably reduced. From Kinderhook formation, Le Grand, Iowa. (Courtesy of the University of Chicago.)

eight, or multiples of six or eight. Most of the Paleozoic types were "cup corals" (solitary forms, "honeycomb corals" (compound), and "chain corals" (compound) (Fig. 267). Corals are, and always have been, marine animals.

*Echinoderms,* often called the "Starfish" family, are marine forms with a distinct body cavity, a very simple digestive canal. a low-order nervous system, and a water circulatory system. They are nearly always radially segmented. They ranged throughout the Paleozoic, the most primitive (stalked) forms only having existed during the Cambrian. Beginning with the Ordovician, more complicated stalked forms (crinoids), popularly called "stone lilies," appeared and they have persisted to the present day. They are (and were) animals with a complex, highly segmented, headlike portion attached to the sea bottom by a long segmented stem (Fig. 268). The segments are of carbonate of lime. They were especially profuse during Silurian and Mississippian times when, on certain parts of the sea bottom, they must have existed as miniature forests. The well-known five-pointed "starfishes" have existed with remarkably little change from Ordovician time to the present. So-called "sea urchins" live in basket-shaped, segmented, carbonate of lime shells covered with bristling movable spines. They are first known from the Ordovician, but they did not become abundant or very diversified until Mesozoic time.

FIG. 269. Various Ordovician bryozoans on a slab of limestone. (After R. S. Bassler, U. S. National Museum.)

*Worms* are known to have existed since late Proterozoic days. Tracks and borings make up most of their fossil record. They have seldom been well fossilized because of their softness, and they are not particularly interesting from the standpoint of evolution.

The sub-kingdom of animals called the *molluscoids* consists of two

important types, the simple bryozoans (or "sea mosses") and the higher brachiopods. In outward appearance the *bryozoans* somewhat resemble modern corals, but they are distinctly more complex in structure (Fig. 269). They, like modern corals, are colonizers. They have ranged from Ordovician time to the present with but little change during those long ages. Their tiny carbonate of lime skeletons have often helped to build up great limestone formations.

*Brachiopods* have two distinct shells operating on a hinge and enclosing the soft body of the animal. The body has a considerable differentiation of parts, but without eyes or distinct head. A plane passed through the middle of the hinge line, and at right angles to it, cuts the shells into two parts exactly alike. In other words the shells are bilaterally symmetrical (Fig. 270). The shells have nearly always been less than two inches long. Brachiopods have ranged from earliest Paleozoic time to the present. At least 7000 species are known, most of them from the Paleozoic rocks. Relatively few now exist. By studying their gradual changes in species they have come to rank among the most valuable fossils as geologic time markers and for purposes of correlation. From the evolutionary standpoint it is an interesting fact that the very early Paleozoic forms were small, and primitive (or low-order) with their shells not working on hinges. Later in the Paleozoic they became larger and more highly organized with much thicker shells most of which worked on straight hinges.

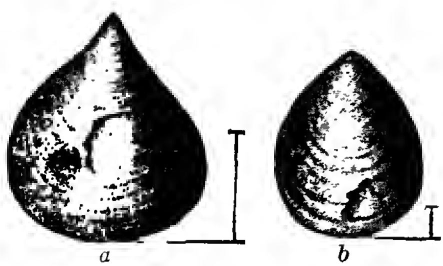



FIG. 270. Cambrian brachiopods: *a, Lingulella prima*; *b, Lingulella acuminata.* (After Walcott.)

The *mollusks* are still more highly organized than the molluscoids, having more or less well-developed heads and locomotive organs. They are very abundant and diversified today, and many thousands of species are known only in fossil form. The simplest of these are the *pelecypods* which, like the brachiopods, live between two shells working on a hinge, but unlike the brachiopods, these shells are not symmetrical with reference to a plane cutting them at right angles to the hinge line. Cambrian rocks contain the oldest known fossil pelecypods, and these were small, rare, and thin-shelled. They developed greatly during Paleozoic times. Modern pelecypods include clams and oysters.

*Gastropods* (snails) possess distinct heads, eyes, and tentacles. They inhabit one-chambered, more or less coiled shells. They have ranged from earliest Paleozoic time to the present (Fig. 273). A remarkable

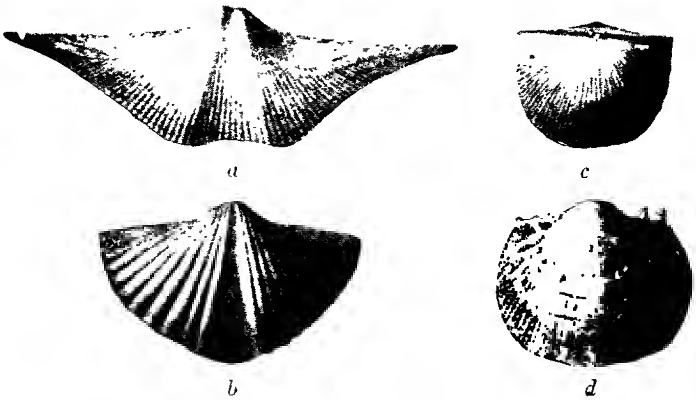


FIG. 271. Devonian brachiopods: *a, Spirifer disjunctus*; *b, Spirifer intermedius*; *c, Stropheodonta demissa*; *d, Productus Hallanus.* (All from Md. Geol. Survey.)

fact about them is that through all of those many millions of years they have persisted with no really conspicuous evolutionary change.

The *cephalopods* represent the highest mollusks with well-defined

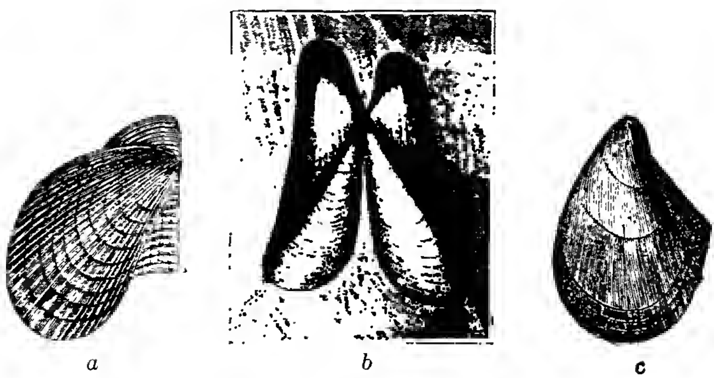


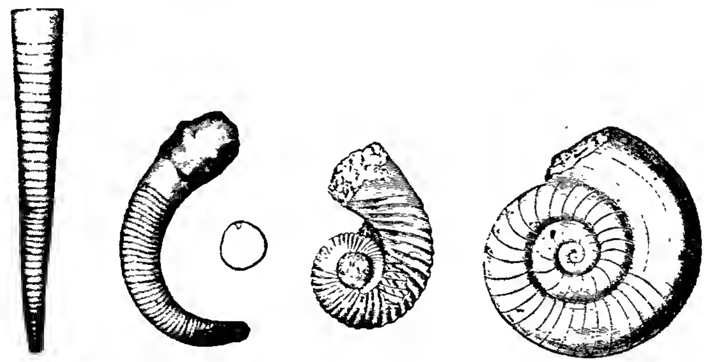
FIG. 272. Ordovician pelecypods: *a, Cardiola interrupta* (Hall); *b, Orthodesma? subcarinatum* (Ruedemann); *c, Ambonychia bellistriata* (Hall).

foot structures, heads armed with tentacles, and large complex eyes. The more primitive forms are the chambered cephalopods, so called because the external shell is divided into compartments which are suc-

cessively built up and abandoned by the animal as it grows. The higher (non-chambered) types did not exist in the Paleozoic. For two reasons the chambered cephalopods constitute one of the most interesting illustrations of evolutionary changes, ranging from early Paleozoic time to the present, first because there is such an abundant record in the rocks of all these ages, and second because the evolutionary changes have expressed themselves in the external or shell portions in a remarkable and easily recognizable manner. Beginning in the Cambrian, they were very primitive, straight or curved forms with simple partitions separating the compartments. In the Ordovician important advances were made giving rise to more curved forms, open-coil and close-coil forms (Fig. 274). At the same time the straight forms came to be the largest and most powerful

a b

FIG. 273. Cambrian gastropods: *a, Matherella saratogensis*; *b, Pelagiella minutissima*. (After Walcott.)



a b c d

FIG. 274. Ordovician cephalopods: *a, Orthoceras sociale* (Hall); *b, Cyrtoceras neleus* (Hall); *c, Trochoceras-like* form (Silurian specimen after Barrande); *d, Trocholites ammonius* (Hall).

animals in the Ordovician world, some of the shells reaching lengths of 10 to 15 feet. The straight forms declined during the middle and late Paleozoic and became extinct in the early Mesozoic. During the middle Paleozoic the close-coiled forms developed angular partitions (Fig. 275), and in the later Paleozoic the partitions were still more complex (Fig. 276).

*Arthropods* comprise the highest sub-kingdom of all invertebrate animals. They are characterized by longitudinal body segmentation, jointed appendages, and usually a pair of nerve centers in each segment. The simplest forms are the *crustaceans* (e.g. lobsters) which breathe by means of gills or through the body, have well-developed feelers, and a thin shell cover. The wholly extinct race of *trilobites,* classed among low-order crustaceans, were among the most common, interesting, and geologically important of Paleozoic animals (Fig. 277). They began in the earliest Paleozoic, reached their culmination of development before the middle of the era, and became extinct by the close of the era. They were inhabitants of the sea. In early Paleozoic time they were among the most highly organized of all animals, and they were progenitors of

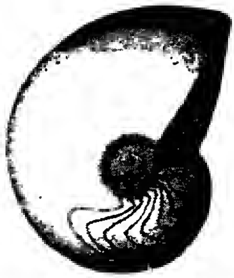


FIG. 275. A Devonian goniatite, *Manticoceras pattersoni.* (After Hall.)

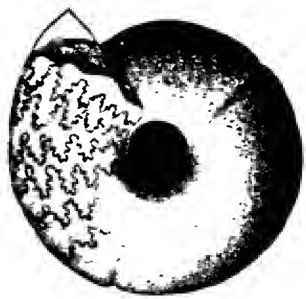


FIG. 276. A Permian chambered cephalopod, *Waagenoceras cumminsi* (White) showing highly folded suture (partition) lines.

later and higher types of arthropods. They were remarkably varied in size and form, ranging in length from less than an inch to two feet. Thousands of species have been found in the Paleozoic strata.

An extraordinary form of arthropod, belonging to the class of *arachnids,* was the *eurypterid* or so-called "sea scorpion" (Fig. 278) which ranged throughout the Paleozoic in a great variety of forms. Their pairs of appendages grew out of the head plate only, thus differing from the trilobites. Modern scorpions are related to them. They culminated in size in the middle Paleozoic when some individuals attained lengths of six to eight feet. True *scorpions* appeared in the Silurian. As far as known, they were the earliest land or air-breathing animals to inhabit the earth. True *spiders* appeared in the Pennsylvanian.

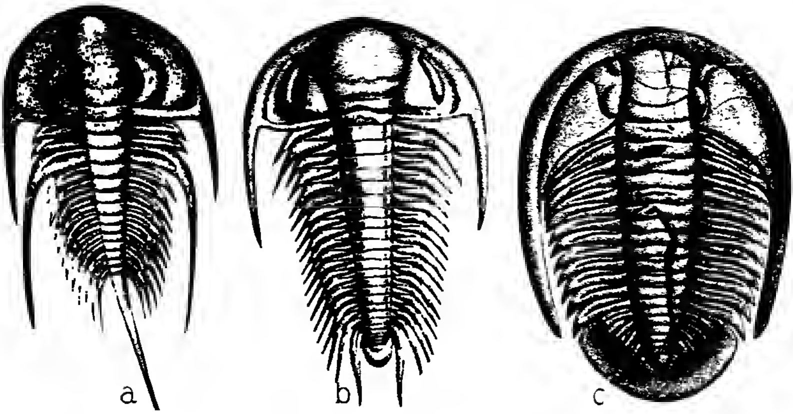



FIG. 277. Cambrian trilobites, restored forms: *a*, *Olenellus gilberti*, characteristic of the Lower Cambrian; *b*, *Paradoxides bohemicus*, characteristic of the Middle Cambrian; *c*, *Dikellocephalus pepinensis*, characteristic of the Upper Cambrian. (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company.)

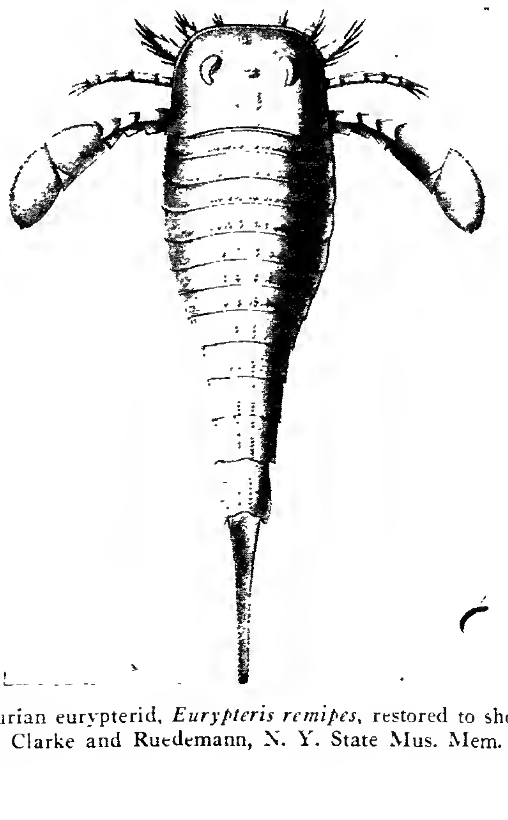


FIG. 278. A Silurian eurypterid, *Eurypteris remipes*, restored to show upper side. (After Clarke and Ruedemann, N. Y. State Mus. Mem. 14.)

*Insects* comprise the highest forms of arthropods. The oldest known fossil forms occur in Pennsylvania strata from which more than 1000 species have been unearthed. As would be expected, they were all very simple, primitive types such as cockroaches and dragonflies (Fig. 279). Many of them were remarkably large. Cockroaches several inches long, and dragonflies with a spread of wing of over two feet are known to have existed. Development of insects was especially favored during the Pennsylvanian (coal age) time because of the prolific vegetation, but probably they actually came into existence in somewhat earlier time.

FIG. 279. A Pennsylvanian insect, *Corydaloides scudderi* (Brongniart). This insect had a spread of wing of 18 inches. (From Le Conte's "Geology," permission of D. Appleton and Company.)

None of the great variety of higher types of insects lived during the Paleozoic era.

*Vertebrates* constitute the highest sub-kingdom of animals with man at the climax. A vertebral column (usually a backbone) characterizes them. The oldest known vertebrates, found in the Ordovician, were very low-order, primitive forms. These were the ostracoderms (so-called "armor fishes"). Most of them were fishlike in appearance (Fig. 280), but they were more lowly organized than true fishes. Some of them resembled certain arthropods. For these reasons the ostracoderms, or creatures much like them, have been regarded as the connecting link between the invertebrate and vertebrate animals. They were rarely more than six or seven inches long. The vertebral column of the ostracoderms consisted of cartilage, and it extended clear through the tail portion. They were provided with jointed swimming paddles in-

stead of true side fins of fishes. Ostracoderms reached their zenith of development in the Devonian and became extinct by the close of that period.

Next higher zoologically, and next to appear in geological time, were the *fishes*. Also, the first known fishes were very low-order types (e.g. sharks) in the Silurian. In these respects, therefore, the fishes perfectly

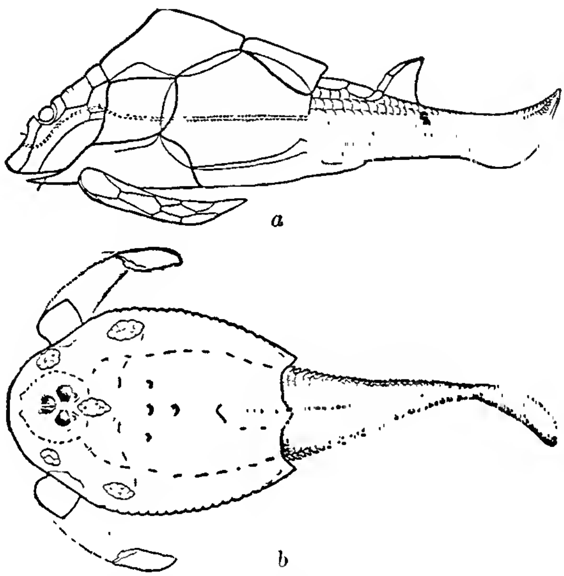


FIG. 280. Devonian ostracoderms: *a*, *Pterichthys testudinarius*, restored (Dean after Woodward); *b*, *Tremataspis*, restored (after Patten).

illustrate the well-known law of evolution, namely, that animals appeared in geological time in an increasing order of complexity of organization. The fishes showed such a tremendous development into numerous species and countless individuals during the Devonian that the period has long been known as the "Age of Fishes."

Very representative of the Devonian fishes were sharks, arthrodirans, dipnoans, and ganoids. *Sharks*, then as now, had wholly cartilaginous skeletons and they were not covered with scales or plates. The remarkable *arthrodirans* have long since become extinct. Bony armor-plates covered the fore part of the body (Fig. 281). Some of them

were 20 to 25 feet long. They were probably the rulers of the Devonian seas.

The *dipnoans* were remarkable in being able to breathe in both water and air. Their limblike fins and lung sacs were more like amphibian than fish features (Fig. 281). Modern descendants are rare.

*Ganoids* were the most abundant and highly organized fishes of the time. They were characterized by a covering of small bony plates which did not overlap each other as in typical modern fishes. Their

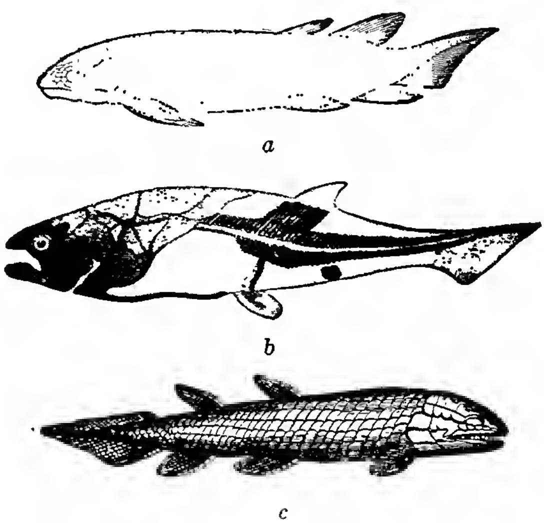


FIG. 281. Devonian fishes: *a*, Dipnoan, *Dipterus valenciennesi* (restored by Traquair); *b*, Arthrodiran, *Coccosteus decipiens* (restored by Woodward); *c*, Ganoid, *Osteolepis* (restored by Nicholson).

complex tooth structure, skull bones, and limblike fins were distinct amphibian features (Fig. 281).

The following statements in regard to Devonian fishes are of particular evolutionary significance:

(1) All were of simple types. The most typical and highly organized, true bony fishes, so common today, did not exist in the Devonian, and even the ganoids were of primitive types.

(2) All had cartilaginous skeletons. The vertebral column and other portions of the skeleton were not ossified (i.e. changed to bone).

(3) All had vertebrated tail fins. The vertebral column extended

through the tail fin and gave off fin rays to support a lobe above and below. Sometimes this tail fin was symmetric and sometimes asymmetric. The asymmetric form is regarded as the more primitive. Most modern fishes (teleosts) have non-vertebrated tail fins, the fin rays being sent out from a plate at the end of the vertebral column.

(4) They were generalized types. That is to say, combined with their characteristics of true fishes were other features connecting them with still higher (amphibian) forms of animals.

During later Paleozoic time the fishes, underwent no outstanding evolutionary change.

*Amphibians* take rank next above the fishes, having evolved from certain types of the latter in mid-Paleozoic time. Footprints only are known in the Devonian rocks, but Mississippian, Pennsylvanian, and Permian strata have yielded many and varied fossil forms. Then as now they breathed by gills when young and by lungs when adult, and they had large, bony, rooflike skull plates. Amphibians are relatively unimportant among the vertebrates of today, but in later Paleozoic time they reached their culmination in numbers, complexity, and diversification of size and forms. Many of them were then small creatures somewhat like their nearest living relatives—the salamanders. Many other forms were among the gigantic land vertebrates of the time, some having reached lengths of 6 to 8 feet (Fig. 283).

*Reptiles* are still higher animals than the amphibians, and they appeared on earth at a still later time. They never have gills, they always have bony scales or plates developed in the skin, and they constitute the highest forms of cold-blooded animals. Reptiles developed from the amphibians in late Paleozoic time. Reptilian amphibians of the Pennsylvanian evolved into a large variety of true reptiles of the Permian, some of which were over 8 feet long (Fig. 284). An important fact, from the standpoint of evolution, is that Permian reptiles already began to show certain distinct characteristics of the still higher mammals. Birds and mammals were not in existence before the end of the Paleozoic era.

## General Remarks on Paleozoic Life

Viewed in a broad way, the life of the Paleozoic was distinctly different from that of the succeeding Mesozoic or Cenozoic. Very few species and not many genera passed from the Paleozoic to the Mesozoic,

Fig. 282. Restorations of Late Devonian life of New York. Glass sponges (at left), close-coiled chambered cephalopod (at left middle), straight chambered cephalopod (at right middle), stalked echinoderm or "stone lily" (at right), fishes, asterozoans, and pelecypods. (Courtesy of the New York State Museum.)

and even the larger groups of organisms which did continue usually underwent important structural changes. Paleozoic organisms were the more primitive in structure, and it has been aptly said that they bear

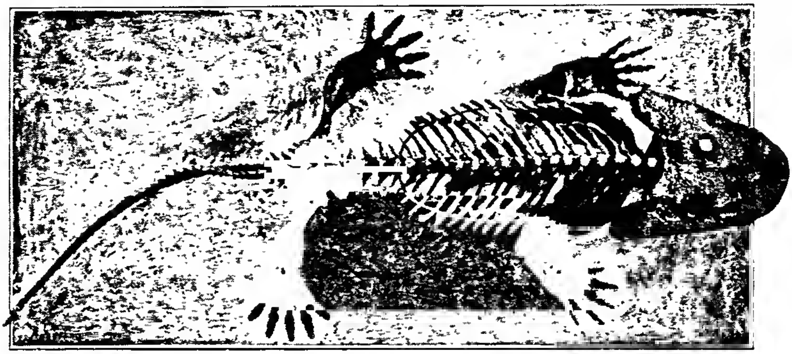


Fig. 283. A Pennsylvanian amphibian (labyrinthodont), *Eryops.* This creature attained a length of 6 or 8 feet. (Courtesy of the American Museum of Natural History.)

somewhat the same relation to the succeeding forms that the embryo does to the adult.

It seems to be a well-established fact that profound changes in the

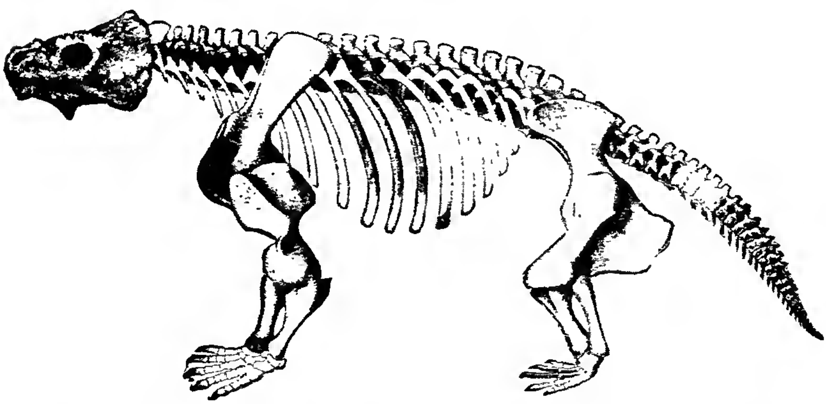


Fig. 284. A Permian reptile, *Pareiasaurus serridens.* This creature reached a length of over 8 feet. (After Broom, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

natural environment have produced fundamental changes in the plant and animal realms. Thus the late Paleozoic and early Mesozoic was a time of one of the most profound and far-reaching physical disturbances

in the known history of the earth. Great mountains were being made in many parts of the world, particularly in eastern North America and in Europe; the lands were much increased in size and height; one of the two greatest known Ice Ages was a feature of the Permian; and the ocean waters were affected in various ways. These physical changes in turn caused climatic changes, altered habitats of plants and animals, and modified sources of food for the animals. Accompanying these changes, the giant lepidophytes, seed ferns, and cordaites became extinct, while higher plants, such as cycads and conifers, began to clothe the earth. Large groups of animals, such as ancient primitive corals, primitive echinoderms, trilobites, and eurypterids, and simple chambered cephalopods, disappeared from the waters; amphibians culminated; and modern (complex) corals, complex chambered cephalopods, insects, reptiles, and mammals made their appearance.

It is a very significant fact, from the standpoint of evolution of life on the planet, that very few if any species of either plants or animals of Paleozoic time have continued to exist to the present day. In other words, since the Paleozoic era closed, all life, in regard to its myriads of species, has undergone a practically complete revolution.

## CHAPTER XXI

## MESOZOIC ROCKS AND HISTORY

### Triassic Period

**Triassic Rocks.** The accompanying map (Fig. 285) shows the surface distribution of both the Triassic and Jurassic rocks in North America. The Atlantic Coast areas are wholly Triassic; the California areas are mainly Jurassic; and the remaining areas include both Triassic and Jurassic rocks which have usually not been carefully separated. There is no reason whatever to believe that Triassic rocks were ever deposited over Canada except along the western coast and to a slight extent in Nova Scotia. Likewise it is not known that Triassic rocks ever occurred in the Mississippi Basin except immediately east of the Rocky Mountains. This is in marked contrast with the Paleozoic systems. Accordingly, the present concealed Triassic rocks and areas of their former presence are largely confined to the regions of existing outcrops.

Triassic rocks (*Newark* series) occupy comparatively small narrow areas just east of and parallel to the Appalachian Mountain range from southeastern New York to South Carolina, and farther northward in the Connecticut River Valley and in Nova Scotia. In the northern areas the rocks are sandstones and shales, with some coarse conglomerates, especially at the base. Because of their prevailing red color and general resemblances to the "Old Red Sandstone" (Devonian) of Scotland, they have been called the "New Red Sandstone." Many of the beds show sun cracks, raindrop pits, ripple marks, and footprints, and remains of land reptiles (dinosaurs). In Virginia and the Carolinas the rocks have a similar lithologic character, though the red color is not so common, and some workable coal beds occur. The fossils, which are mostly plants in the dark shales, point to the Upper Triassic age of the series. The rocks of the series are nearly everywhere somewhat folded, tilted, and extensively fractured by normal faults, and they also contain numerous lava-flaws, intrusive sheets, and dikes.

The Triassic strata of the western interior region are distributed over nearly the same areas as the Permian, and in many places the rocks of these two systems are not at all sharply separated. Nearly all the

known Triassic rocks of the western interior of the United States are located within the cross-lined area on map, Figure 287. They are much like the Permian of this region, but they are even more typical of the so-called "Red Beds." Sandstone and shale, with some conglomerate, limestone, and gypsum, are the predominant rocks. Some of these rocks

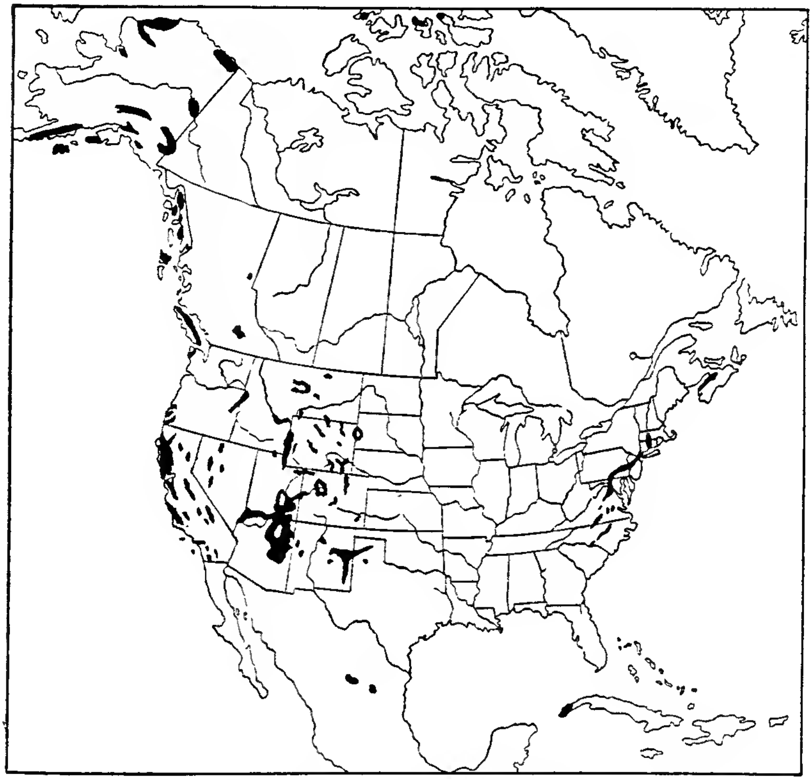


FIG. 285. Map showing the surface distribution (areas of outcrops) of Triassic and Jurassic strata in North America. Some areas of doubtful age and extent not shown in British Columbia. All Atlantic Coast areas are Triassic. In much of the western United States the Triassic and Jurassic have not yet been satisfactorily separated.

are of restricted marine origin, but most of them are of either salt-lagoon or terrestrial origin.

The Triassic strata are locally much folded in the mountains of the western interior, but over wide areas they are nearly horizontal. They are wonderfully and widely exposed in the Colorado Plateau where the

nearly horizontal strata lie from 5000 to 10,000 feet above sea level. Because of their high degree of sculpturing and coloring, as in the Painted Desert of Arizona, they form a striking feature of the landscape (Fig. 288).

The Triassic rocks of the Pacific Coast include the only true marine strata of this age in North America, and they are there extensively developed with practically all portions of the system from oldest to youngest well represented, particularly in California and Nevada. The rocks consist mostly of marine shales, limestones, conglomerates, and sand-

FIG. 286. Tilted Triassic shale and sandstone in the Connecticut Valley, near Holyoke, Massachusetts.

stones. These rocks are often more or less metamorphosed, as in the Sierra Nevada Mountains. The rocks are usually much folded and often faulted in the western mountains. In California, southern Alaska, and British Columbia the system contains great quantities of igneous material, mainly lavas and tuffs, reaching total thicknesses of thousands of feet.

The thickness of the Triassic strata on the Atlantic Coast is from 3000 to fully 15,000 feet; in the western interior from a few hundred to several thousand feet; and on the Pacific Coast from several thousand to 13,000 feet.

**Triassic History.** *Seas and Sedimentation.* Accompanying map Fig. 285, shows the areas of continental deposition in eastern North America during Upper Triassic time. These were all in the general Appalachian region. The non-marine formations of Upper Triassic age clearly show by their distribution and mode of occurrence that they

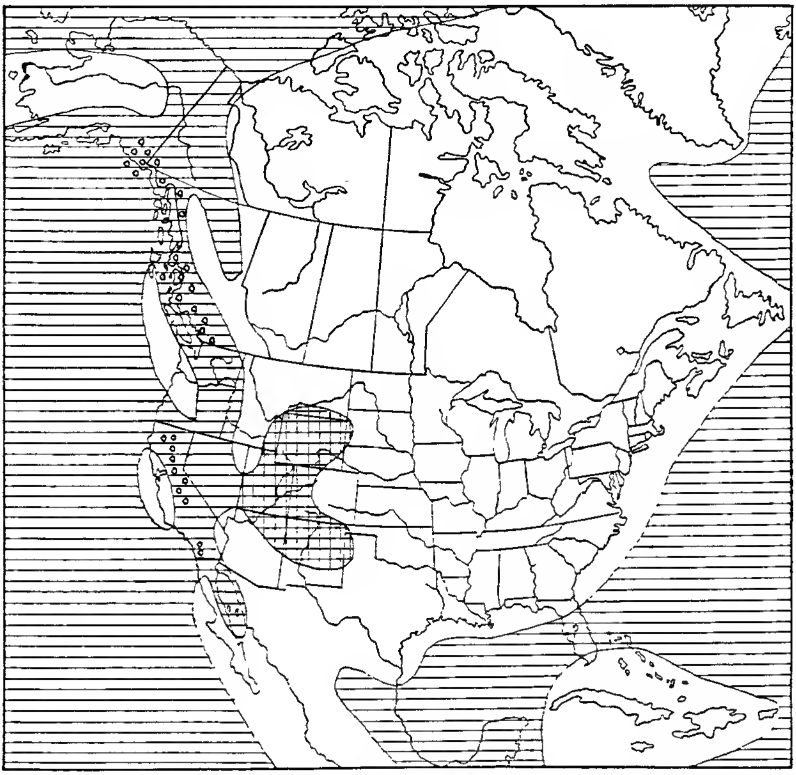


FIG. 287. Generalized paleogeographic map showing sea and land areas in North America during Late Triassic time. This was the greatest Triassic sea. White areas, land; ruled areas, sea; cross-ruled areas, partly modified marine and partly continental conditions. Small circles show volcanic islands in the western sea. Principal data (modified) from maps by B. Willis, C. Schuchert, and E. B. Branson.

were deposited in a series of long, troughlike basins. Because these troughs were situated between the two great land masses—Appalachia and the newly formed Appalachians—the conditions were very favorable for rapid accumulations of thick deposits in them. The great thickness of the strata (maximum, 2 miles or more) strongly points to a sub-

sidence of the basin floors while the deposition was in progress. Most of the rocks are well stratified. The generally red color and freshness of the material in the formations indicate that the climate of the time was arid or semi-arid, and the presence of sun cracks, ripple marks, and tracks of land animals at many horizons show that the beds were laid down in part on land, but mostly under shallow water, such as flood plains and playa lakes, where frequently changing conditions often allowed the surface layers to lie exposed to the sun.

Remarkable reptiles of Triassic time, known as dinosaurs, left numerous footprints on exposed mudflats in various places. In many cases the tracked surfaces, after drying in the sun, were covered by the deposits left by succeeding flood waters. Such tracks are found here and there through thousands of feet of strata, particularly in the Connecticut Valley. Outcrops of these footprint-bearing strata are fine illustrations of the remarkable detail in which some geological records may be preserved.

During the time of deposition of the Triassic beds, there was considerable igneous activity, as shown by the occurrence of sheets of igneous rocks within the mass of sediments. In some cases true lava flows with cindery tops were poured out on the surface and then became buried under later sediments, while in other cases the sheets of molten rock were forced up either between the strata or obliquely through them, thus proving their intrusive origin. As a result of subsequent disastrophism and erosion, these igneous rock masses often stand out conspicuously as topographic features.

In Early Triassic time the Pacific waters spread eastward in the form of a wide gulf over much of northern and eastern California, most of Nevada and Utah, and into southeastern Idaho. During most of the Middle Triassic, Nevada was still submerged under the sea, but the rest of the western interior was land, probably receiving continental deposits here and there. Late Triassic time was marked by the development of a great basin covering a large part of the western interior region. This basin seems to have been a more or less cut off arm of the sea, connected with the Pacific across eastern Nevada (see Fig. 287). Very typical "Red Beds," indicating aridity of climate, were extensively developed in this basin. Modified marine, great salt lagoon, salt lake, and even terrestrial conditions seem to have prevailed from time to time in this basin.

Viewed broadly, there was a progressive submergence of much of the Pacific Coast of North America during Triassic time. Early in the

period most of California and Nevada were submerged under the sea; in the middle of the period there was added a wide embayment over much of British Columbia and the southern end of Alaska; and in the Upper Triassic almost the whole Pacific Coast area from central Lower California to southwestern Alaska was under the sea. There was probably also a connection with the Arctic Ocean across eastern Alaska.

FIG. 288. Horizontal "Red Beds" consisting of interbedded red sandstone and shale with numerous concretions. Near Tuba City, northern Arizona.

Figure 287 shows the extent of the greatest North American Triassic sea.

In much of California, western British Columbia, and southern Alaska submarine volcanic activity took place on a tremendous scale in later Triassic time as proved by the direct association of thousands of feet of lavas and tuffs with marine strata.

*Close of the Triassic.* The Triassic closed in eastern North America with crustal disturbances which raised the basins of deposition of the Triassic Rocks into dry land, and broke the strata, and associated lavas and intrusive sheets, into a great series of tilted fault-blocks, thus leaving all of the eastern half or two-thirds of the continent dry land and undergoing erosion.

"Red Beds" probably continued to accumulate over the western interior region. There seems to be clear evidence that marine waters withdrew from the Pacific Coast region during latest Triassic time.

**Triassic Climate.** The extensive areas of "Red Beds," often accompanied by salt and gypsum, in the western interior and eastern North America, northern and western Europe, and northern Africa show widespread aridity of climate in the northern hemisphere during the period. There is no evidence of glaciation, and the fossils indicate general mildness of climate, except at the close of the period when the temperature was distinctly lower than usual. Judging by the character and distribution of the fossils, the water of the Arctic Sea was appreciably cooler than that of lower latitudes, so that climatic zones must have been defined to some extent at least.

## Jurassic Period

**Jurassic Rocks.** Differing from all preceding systems, rocks of undoubted Jurassic age are wholly confined to the western part of the continent. The black portions of Figure 285 contain nearly all of the numerous areas of outcrops of Jurassic rocks in western North America.

The Jurassic strata of the Pacific Coast, from southern California to southwestern Alaska, are largely of marine origin. Various kinds of strata are represented, and these are usually somewhat metamorphosed and much folded and faulted. Dark slates are perhaps the most common. The strata are nearly everywhere closely associated with igneous material, this being particularly true in British Columbia where the Jurassic system is unusually thick and volcanic rocks constitute about one-half of it.

Tremendous bodies of granite (or rather "granodiorite") of Late Jurassic age occur throughout the Pacific Coast region from western Mexico well into Alaska (Fig. 291). These intrusions occurred at the time of the Sierra Nevada Revolution (see beyond). Granodiorite of this age is wonderfully exposed in the walls of Yosemite Valley, California, and elsewhere in the Yosemite National Park (Fig. 292).

In the western interior of the continent, Triassic and Jurassic strata often have not been satisfactorily separated, but extensive "Red Beds" (with gypsum) of continental origin, like those of the Triassic system of the region, are doubtless of Jurassic age. In the walls of Zion Canyon, Utah, a continental formation of nearly horizontal, massive sand-

stone over 2000 feet thick is wonderfully exposed. It is red in its lower portion, and white in its upper portion. The lower part of this great formation may possibly belong to the Triassic.

The only known true, marine, Jurassic strata in the western interior are of Upper Jurassic age. These marine rocks comprise all types of ordinary sediments, especially limestones and shales, usually much folded in the mountain regions. All of the Upper Jurassic marine strata of the western interior of the continent occur within the area represented as having been occupied by sea water on Figure 290. Overlying the

FIG. 289. Rainbow Natural Bridge near the middle-southern boundary of Utah. This great rock arch, over 300 feet high, has been carved out of red Jurassic sandstone. (Photo by H. E. Gregory, U. S. Geological Survey.)

marine Jurassic in the western Great Plains region there is a very late Jurassic formation of continental origin and remarkable because so many remains of great reptiles have been found in it.

The thickness of the system in California is known to reach fully 15,000 feet, while in western Nevada 5000 to 6000 feet of limestones and slates are reported. In Alaska a maximum thickness of 15,000 feet has been found, and in British Columbia, 18,000 feet. Throughout the western interior the thickness never appears to be great, usually not more than a few thousand feet.

**Jurassic History.** *Seas and Sedimentation.* The Pacific coast region seems to have been above sea level in earliest Jurassic time. Then the waters encroached upon the land, covering the Pacific Coast region from the south end of Lower California to southwestern Alaska. The sites of the Sierra Nevada, Cascade, and Coast Ranges were then sea-

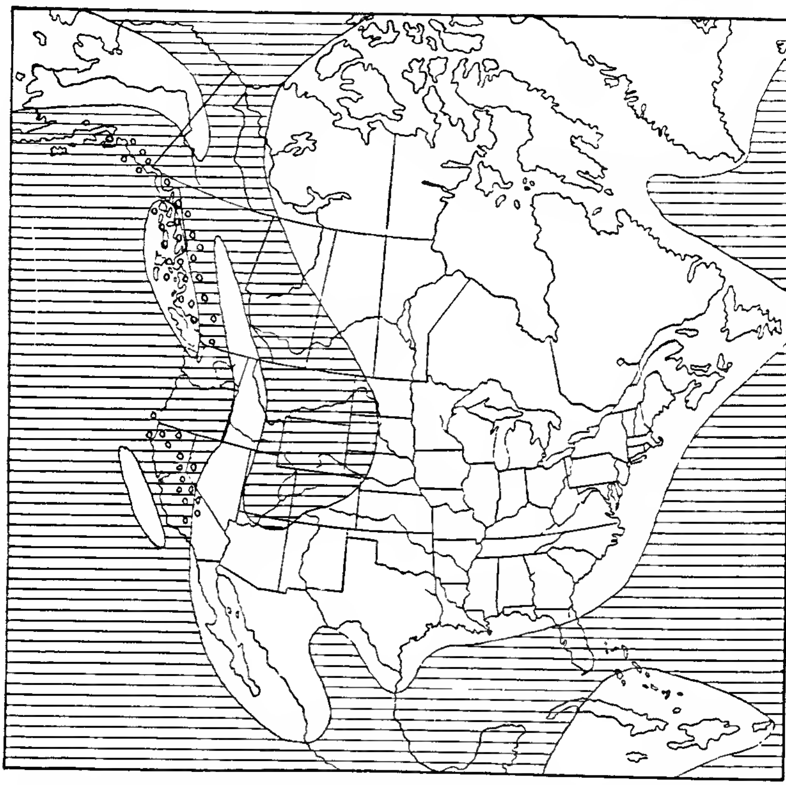


FIG. 290. Generalized paleogeographic map showing sea and land areas in North America during the early part of Late Jurassic time. White areas, land; ruled areas, sea. This was the greatest Jurassic sea. Small circles show the general distribution of Middle and Late Jurassic volcanoes. Principal data (modified) from maps by C. Crickmay and C. Schuchert.

covered. Barring relatively minor changes, the marine waters became more extended until they reached the climax for the period. This was in the earlier part of Late Jurassic time (Fig. 290), at which time the island region of British Columbia seems to have been a land area.

As in the Triassic, tremendous volcanic activity, most of it submarine or on volcanic islands, occurred. "Toward the end of Lower (Early)

Jurassic time volcanoes appeared along a great belt from southern Alaska, through the Coast Range region of British Columbia, and into California. Great beds of agglomerate and flows of lava piled upon each other on a sinking earth's surface. For one brief spell, in the early Middle Jurassic, the violent eruptions ceased, and during this interval the sea spread over most of the lava-devastated areas, and left marine deposits. But shortly these were again buried beneath the products of renewed eruptions until thousands of feet of lavas and pyroclastics had accumulated." (C. H. Crickmay.)

During Early and Middle Jurassic times there was deposition of continental "Red Beds" material over much of the central portion of the western interior, especially in the states of Wyoming, Colorado, Utah, northern Arizona, and northern New Mexico. These rocks are excellently exposed in the Colorado Plateau where they are usually 2000 to 3000 feet in thickness. The remarkable cross-bedding of sandstone formations 2000 or more feet thick, such as the *Navajo* sandstone, strongly points to their wind-blown origin on a grand scale.

An important change occurred in the Late Jurassic, namely, the spread of a shallow sea southward from the Arctic Ocean to the east of Alaska and south to northern Arizona. This arm of the sea, or great mediterranean, was 600 miles wide in the western interior of the United States, and considerably narrower in Canada as shown on the map (Fig. 290). Well before the close of the period, the interior sea vanished, and renewed "Red Beds" deposition occurred.

No Jurassic strata now occur in the eastern two-thirds of North America and we have no evidence that any ever were deposited there, hence that vast area was dry land undergoing erosion during the whole period. The period was ushered in by a considerable upwarping of the Atlantic border accompanied by some faulting and tilting, particularly of the Triassic rocks. That this uplift actually occurred, and that the Jurassic period in the eastern United States was a time of extensive erosion, is well established, because the whole Atlantic seaboard, including the tilted and faulted Triassic strata, was worn down toward the condition of a peneplain and the next sediments (Lower Cretaceous) were deposited upon the eastern portion of that worn-down surface.

*Close of the Jurassic (Sierra Nevada Revolution).* The close of the period witnessed profound geographic changes in the western part of the continent. During both the Triassic and Jurassic periods, as well as throughout much of Paleozoic time, there had been more or less continuous deposition of sediments on the Pacific slope over the sites of

the present Sierra, Cascade, and Coast Range Mountains. Toward the close of the Jurassic period these thick sediments, particularly in the Sierra region, were subjected to a tremendous force of lateral compression, the strata being upheaved, folded, and crumpled. Thus the Sierra Nevada Mountains of California were borne out of the ocean and the Pacific shoreline was transferred to the western base of the newly formed

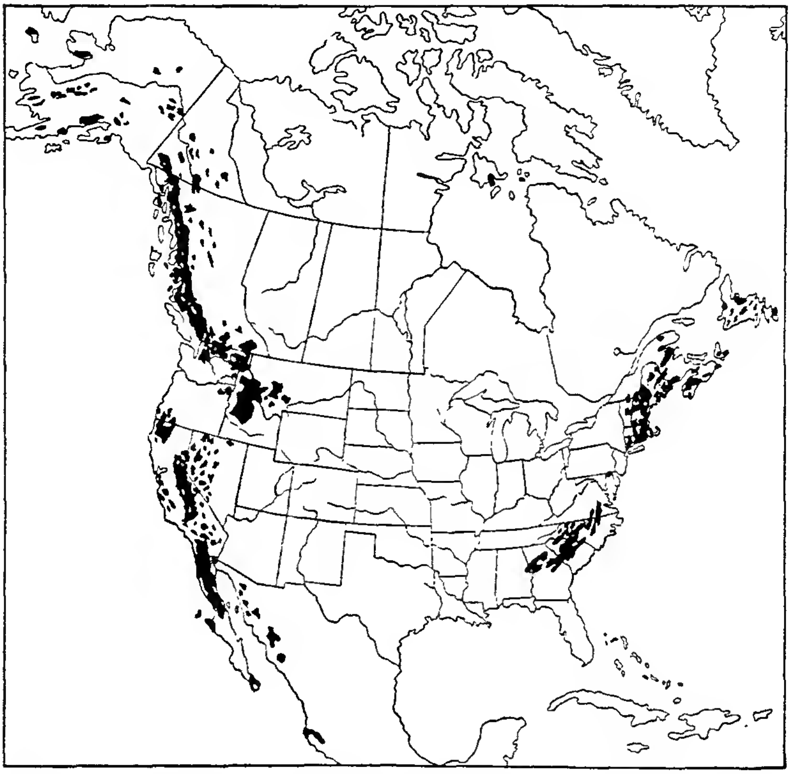


FIG. 291. Map of North America showing (in black) the principal outcropping Paleozoic and Mesozoic batholiths. Those of the west are nearly all of Late Jurassic age, and those of the east are Late Permian with more or less associated Devonian intrusive bodies in New England and northeastward.

range. The Sierra Nevada Mountains, in this their youth, were most likely a lofty range but they were later much worn down by erosion, their present great altitude having been produced by later (Cenozoic) movements.

The best evidence indicates that this orogenic disturbance also affected the strata of the Humboldt and other ranges of western Nevada;

the mountains of southern California; the Klamath Mountains in northwestern California; and the Cascade Mountain region through Oregon and Washington, and, to a notable extent, British Columbia. It is perhaps not too much to say that the whole Pacific Coast of the United States, and probably most of the west coast of the continent, was more or less profoundly affected by the Sierra Nevada Revolution.

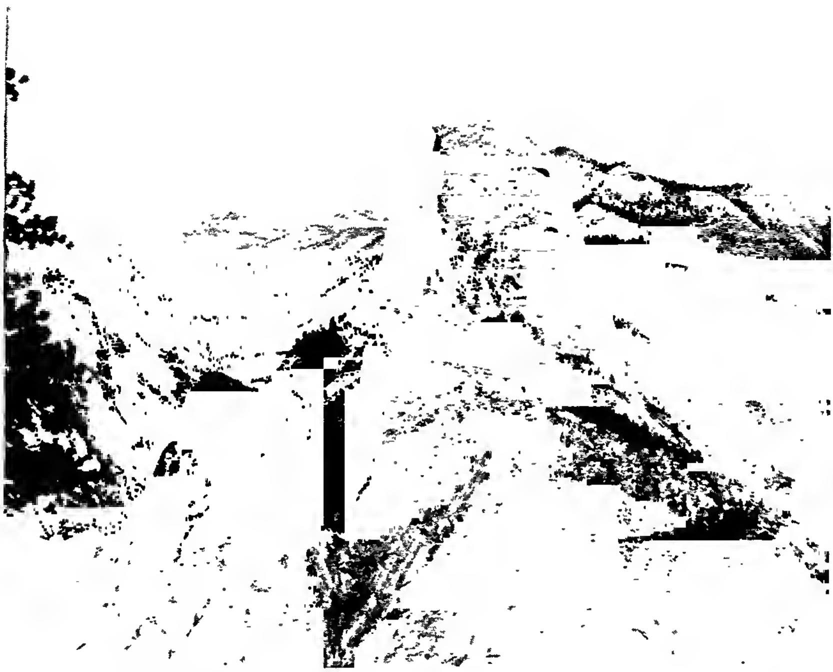


FIG. 292. Half Dome (altitude, 8852 feet) and part of the Sierra Nevada Range as seen from Glacier Point in Yosemite National Park. Practically all the rock in view is Late Jurassic granite (or granodiorite) forming part of the great Sierra Nevada batholith which was intruded at the time of the Sierra Nevada Revolution, and since laid bare by erosion. (Photo by F. E. Matthes, U. S. Geological Survey.)

The strata occupying the site of the present Coast Ranges were somewhat deformed, but probably only enough to form a chain of islands or a very low mountain range. This is proved by the fact that Lower Cretaceous strata are found resting unconformably upon the deformed Jurassic rocks. The orogenic movements which produce the Coast Range Mountains as we now see them came later.

The great arm of the sea or gulf which spread over the western

interior region late in the Jurassic was drained as a result of these crustal disturbances. Hence we learn that all of North America was dry land at the close of the Jurassic period.

Accompanying the Sierra Nevada Revolution, tremendous volumes of granite (or granodiorite) magmas were intruded in the form of numerous large and small batholiths. This was the greatest time of plutonic igneous activity in the post-Proterozoic history of North America. These batholiths, now exposed to view because of profound subsequent erosion, occur throughout most of the Pacific Coast region from western Mexico well into Alaska (Fig. 291). The Sierra Nevada batholith alone is about 400 miles long and 25 to 75 miles wide (Fig. 292), but the British Columbia batholith is very much larger.

**Jurassic Climate.** In general the evidence from the character and distribution of the organisms shows that the climate of the world was somewhat cooler than usual during the Early Jurassic, as indicated by the curbing or dwarfing of various marine animals and land animals and plants. The climate of Middle and Late Jurassic times was, however, characterized by general mildness. Corals, for example, ranged much farther northward then than they do today, and great dinosaurian reptiles roamed regions as far north as Montana.

## Cretaceous Period

**Cretaceous Rocks.** The very great surface distribution of strata of known Cretaceous age is shown on the accompanying map (Fig. 293). Upper Cretaceous strata are much more widely developed and more extensively exposed at the surface than those of Lower Cretaceous age. No system of strata, from the Cambrian to the present, is so extensively exposed as the Cretaceous. The Tertiary system, counting both volcanic and sedimentary rocks, is about as widely exposed.

Cretaceous strata form a narrow outcropping belt along the western side of the Atlantic Coastal Plain, with the exception of parts of Virginia and North Carolina where younger strata completely conceal the Cretaceous. Passing eastward from the exposed belt, well borings show that a large part of the whole Coastal Plain is underlain with Cretaceous strata. "The sediments in general form a series of thin sheets which are inclined seaward, so that successively later formations are encountered in a journey from the inland border of the region toward the coast." The northernmost Cretaceous exposures are on Martha's Vineyard, Massachusetts.

In a similar way, in the Gulf Coastal Plain (including Mexico) the widely outcropping Cretaceous strata (Fig. 293), dipping gently toward the coast, are known to be extensively developed under cover of later formations. In general, therefore, the actual extent of Creta-

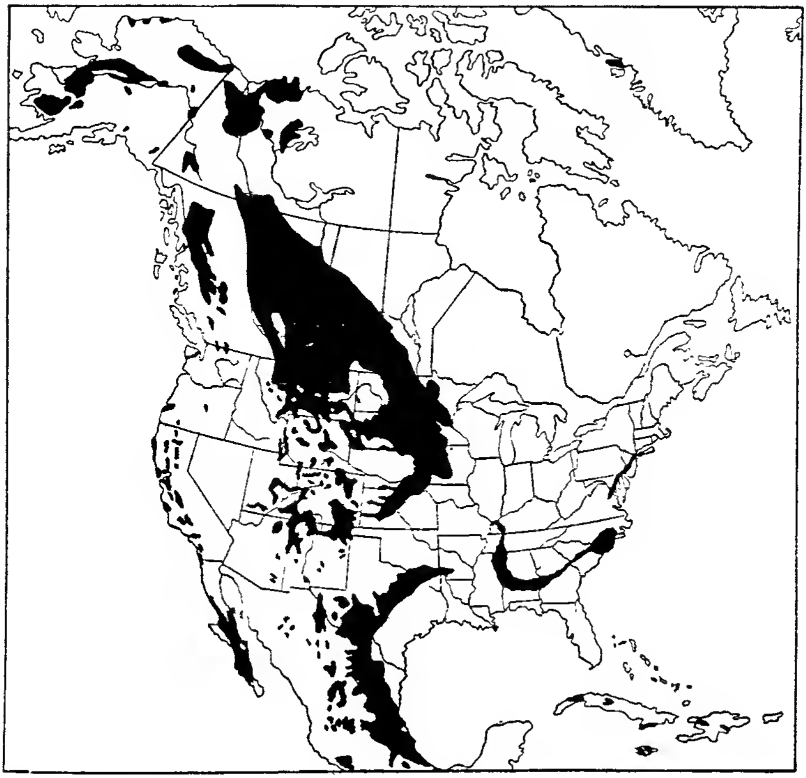


FIG. 293. Map of North America showing the surface distribution (areas of outcrops) of Cretaceous strata. The large and small areas in the western interior of the continent very largely represent Upper Cretaceous deposits.

ceous strata in the Atlantic and Gulf Coastal Plains is much greater than its surface exposures.

A large part of the western interior of North America shows Upper Cretaceous strata at the surface, but there are only a few small areas of Lower Cretaceous. The very extensively developed Upper Cretaceous strata east of the Rocky Mountains, in both the United States and Canada, form a very large outcropping area (Fig. 293), first, because they have been little deformed by folding or faulting, and, second,

because they have usually not been much covered by later material. Within the Rocky Mountains, however, the Cretaceous strata (very largely Upper Cretaceous), because of more or less folding and subsequent deep erosion, show a patchy areal distribution. In the Colorado Plateau the rather widely exposed and comparatively little deformed Cretaceous strata have been much cut into by erosion. Large and small bodies of Cretaceous are concealed under later rocks in many parts of the western interior of the continent.

On the Pacific Coast of the United States, relatively small areas of

FIG. 294. Early Upper Cretaceous marine beds of limestone and shale which were laid down in the great interior sea. Near Thatcher, Colorado. (Photo by N. H. Darton, U. S. Geological Survey.)

outcrops of both Lower and Upper Cretaceous sediments show, but, because the rocks are there usually in a highly deformed condition, they are really much more extensive than the surface areas. The Cretaceous system is most remarkably developed in California where some of its formations are many thousands of feet thick. If all the maximum thicknesses of the different Cretaceous formations of California are combined, the total is nearly 90,000 feet. This is a truly amazing figure, but it should of course be understood that no single section in any region shows such a thickness. In many places, however, thicknesses of 10,000

to 20,000 feet are common, and 40,000 to 50,000 feet of Cretaceous strata are said to occur in the Coalinga (California) district alone.

Cretaceous rocks are widely exposed in Mexico (including Lower California), western British Columbia, western Yukon Territory, and

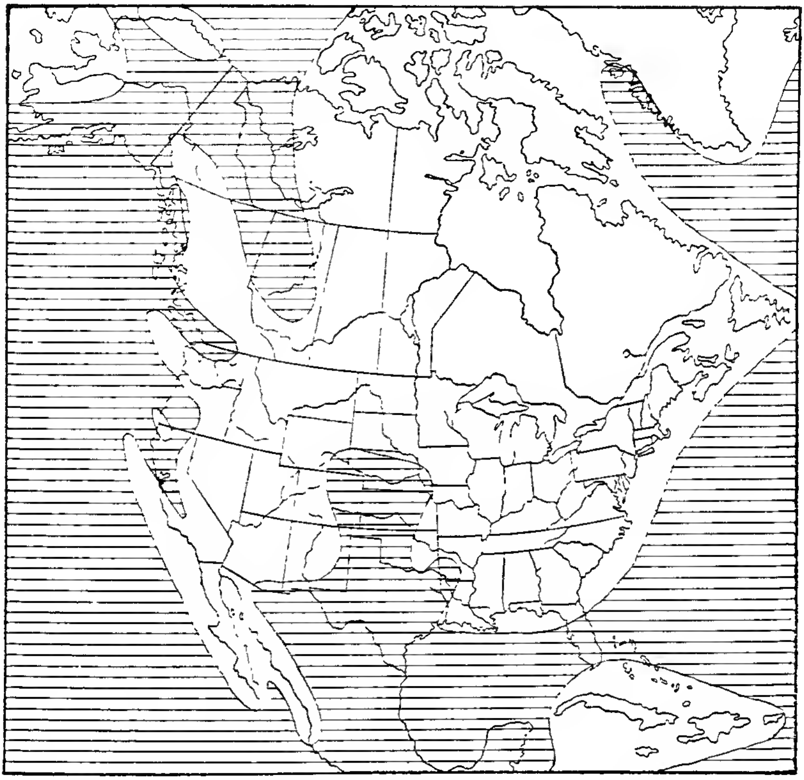


FIG. 295. Generalized paleogeographic map showing sea and land areas in North America during the later part of Early Cretaceous time. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

Alaska in all of which there is often a patchy distribution which has resulted from much erosion of the more or less deformed rocks.

The Cretaceous system shows a maximum thickness of fully 1700 feet on the north Atlantic Coast; 2500 feet in the eastern Gulf region; 3500 to 7500 feet in the western Gulf region; 10,000 to 20,000 feet in the western interior region, though usually much less in any one locality; and 25,000 to 50,000 feet in California.

Volcanic rocks are associated with the Lower Cretaceous in British Columbia, and with the Upper Cretaceous in Texas. Igneous rocks (chiefly lavas) of Late Cretaceous and Early Tertiary ages occur in

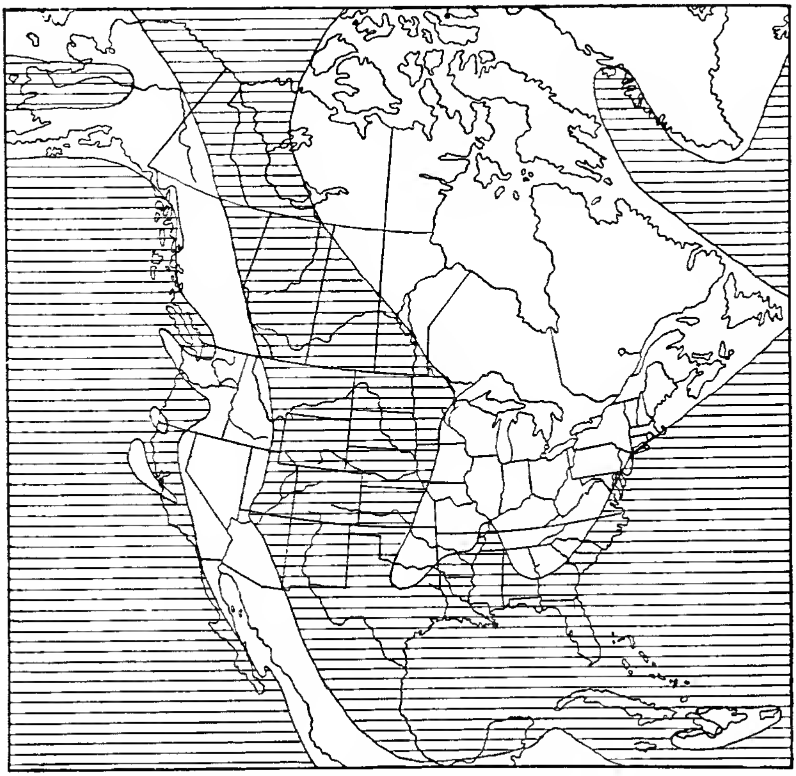


FIG. 296. Generalized paleogeographic map showing sea and land relations in North America during the earlier part of Late Cretaceous time. This was the greatest Mesozoic sea. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

vast quantities in the Rocky Mountain-Great Plains region of the United States.

**Cretaceous History.** *Seas.* Cretaceous time was characterized by a gradual encroachment of the sea upon the continent, reaching a grand climax in the earlier part of Late Cretaceous time, and then gradually waning to disappearance. During Late Cretaceous time North America was cut in two by a vast sea connecting the Gulf of Mexico with the Arctic Ocean. This was the greatest of all Mesozoic or Ceno-

zoic epeiric seas, and it was the last time that marine conditions ever prevailed well within the interior of the continent. In still later Cretaceous time the sea-covered areas gradually became smaller, leaving all land at the end of the period.

The Cretaceous period opened with the coastline of the eastern United States somewhat farther out than it now is, but, early in the period, there was enough subsidence, or possibly warping, of the coastal lands to allow deposition of sediments over much of what is now known as the Atlantic Coastal Plain. That but little downwarping of the surface was necessary in order to produce proper conditions for this sedimentation is evident, because the coastal lands just prior to the Cretaceous were already low-lying as a result of the long Jurassic erosion interval. There was just enough warping of the low coastal lands to produce wide flats, flood plains, shallow lakes, and marshes back from the real coastline. Over such areas were deposited the sediments derived from the Piedmont Plateau and Appalachian areas. The very irregular arrangement of the deposits and their rich content of fossil land plants afford conclusive evidence that the sediments were laid down under continental conditions. In Early Cretaceous time the eastern Gulf Coastal Plain region seems to have been a land area undergoing erosion.

The rather widespread unconformity between the Lower and Upper Cretaceous in these regions proves that, about the close of the Early Cretaceous, there must have been enough emergence of the lands to convert the basins of deposition into areas of erosion. Early in the Late Cretaceous, however, a submergence of the coastal lands took place, inaugurating the deposition of the Upper Cretaceous strata. The general character, mostly marine origin, and present extent of these deposits prove that the submergence allowed a shallow sea to spread over much of what is now called the Atlantic and eastern Gulf Coastal Plain. According to D. W. Johnson, the Late Cretaceous sea also spread westward over the northern Appalachian region, which he believes was already peneplaned, but, if so, all marine deposits laid down in that region have been removed by erosion. In this connection it is very important to note that *Appalachia*, the great land-mass which had persisted through the many millions of years of the Paleozoic era as well as most of the Mesozoic era, largely disappeared under the Cretaceous sea not again to appear in anything like its former magnitude.

During most of Early Cretaceous time a clear and unusually deep

epicontinental sea occupied much of Mexico and Texas and immediately adjoining regions. Great chalk deposits were formed in this clear sea. Perhaps the maximum northward extension of this sea took place during late Early Cretaceous time, when marine waters probably reached as far northward as Colorado.

Throughout Late Cretaceous time marine waters appear to have persisted over the Texas area, having been particularly clear during the deposition of chalk in Texas. The eastern one-half of Mexico was also

FIG. 297. Typical exposure of Upper Cretaceous (Selma) chalk in Alabama. (After L. W. Stephenson, U. S. Geological Survey, Prof. Paper 81.)

submerged. There was considerable volcanic activity in the Texas region.

The best evidence seems to show that there was limited deposition in the Rocky Mountain-Great Plains region during Early Cretaceous time, and perhaps none at all (except in the Mackenzie River Basin) during the first half of that time. In the second half of the Early Cretaceous, deposits of continental origin, very much like those of the same age on the Atlantic Coast, were laid down in the middle part of the Great Plains area, that is, in the northern United States and southern Canada. At this same time an arm of the Arctic spread south to

central Alberta and an arm of the Gulf of Mexico spread north into Nebraska (Fig. 295).

Early in Late Cretaceous time, the Rocky Mountain-Great Plains region was the scene of a very extensive marine transgression. In the comparatively clear waters of this sea there were laid down chalky limestones and other deposits. This great marine invasion was one of the most extensive in the known history of the continent. The sea spread from the Gulf of Mexico northward over the Rocky Mountain-Great Plains region to the Arctic Ocean by way of the Mackenzie River Basin. There is no evidence that this vast interior sea had any connection with the Pacific Ocean (Fig. 296). In the middle of Late Cretaceous time, the connection with the Arctic was cut off, and the much narrower sea reached only as far north as northern Alberta. Near the close of the Cretaceous all that remained was a very narrow arm of the sea extending from the Gulf sea in western Texas northward into North Dakota. At the close of the period even this remnant of the great interior sea vanished.

At various times and places during the Late Cretaceous, there was more or less volcanic activity (largely explosive) in the Rocky Mountain-Great Plains region of the United States as proved by the beds of tuff, agglomerate, etc., interbedded with the Upper Cretaceous strata.

On the Pacific Coast, during Cretaceous time, sea waters extended over the areas indicated by Figures 295 and 296. All was land at the close of the period. Rather remarkable physical conditions must have obtained in western California to give rise to such a phenomenal thickness of sediments during this one period. Apparently the explanation is not far to seek, because the newly upraised Sierra Nevada must have undergone vigorous erosion with rapid accumulation of materials in the marine waters which then occupied the sites of the present Great Valley and Coast Range of California. An unconformity, indicating considerable uplift and deformation, usually separates the Lower and Upper Cretaceous in California.

In British Columbia and Alaska the presence of marine strata proves the existence of sea water over the areas indicated on the accompanying maps, though the coal beds show that great swamps or lagoons must have existed locally.

*Close of the Period in the West (Rocky Mountain Revolution).* The close of the Cretaceous period, or, what is the same thing, the close of the Mesozoic era, was marked by one of the most profound and widespread physical disturbances in the history of North America since

pre-Cambrian time. Over the Rocky Mountain district there had been more or less deposition of sediments (both marine and continental) during Proterozoic, Paleozoic, and Mesozoic times. Toward the close of the Cretaceous, there was vigorous deformation, including both folding and dislocations of the strata, not only throughout the Rocky Mountain district in North America from the Arctic Ocean to Central America, but also even along the line of the Andes Mountains to Cape Horn—altogether more than one-fourth of the way around the earth. This great crustal disturbance has been called the "Rocky Mountain Revolution."

The portion of the Rocky Mountains situated in the northern United States and southern Canada suffered the severest deformation, where

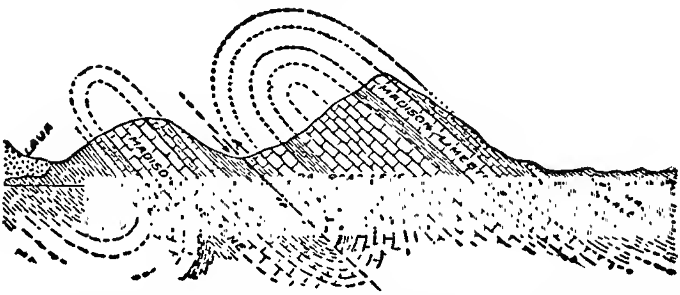



FIG. 298. Structure section in the Rocky Mountains of southwestern Montana showing highly folded Cretaceous and older rocks. After the development of the two overturned folds, the rocks broke along the fault, and the mass on the right was shoved partly over upon the mass on the left. (After U. S. Geological Survey.)

strata 50,000 to 75,000 feet thick were folded and faulted into a mountain range probably no less than 20,000 feet high. Referring to this region Schuchert says that "there had been no orogeny from early Proterozoic time until the close of the Cretaceous. During this vast time there was laid down in this area about 20,000 feet of Mesozoic strata resting upon 26,000 feet of Paleozoic formations, and these in turn lie (almost) conformably upon about 30,000 feet of but little metamorphosed Proterozoic rocks. It is the longest accessible geological section known anywhere and attests to the striking fact that the earth's crust may subside at least 14 miles before it becomes folded into mountains."

The Rocky Mountain orogeny began well before the close of the Cretaceous, and it continued with more or less intensity into the Early Tertiary, but it reached a general climax at the close of the Cretaceous.

Instead of folds, or following the folding, great thrust faults were often developed. A fine example is in Glacier National Park where Proterozoic rocks were pushed at least 10 or 12 miles over Cretaceous rocks on the so-called Lewis thrust fault (Fig. 299). The pile of gently folded Proterozoic rocks (largely strata) involved in the great overthrust block, covers many hundreds of square miles, and reaches a thickness of fully two miles. Because of frictional drag of the over-riding block the underlying, weak Cretaceous strata were usually much folded. Much of the movement along this profound fault probably continued into the Early Tertiary.

Another important physical disturbance accompanying the Rocky Mountain Revolution was considerable igneous activity—both plutonic and volcanic—which continued into the early part of the Tertiary.

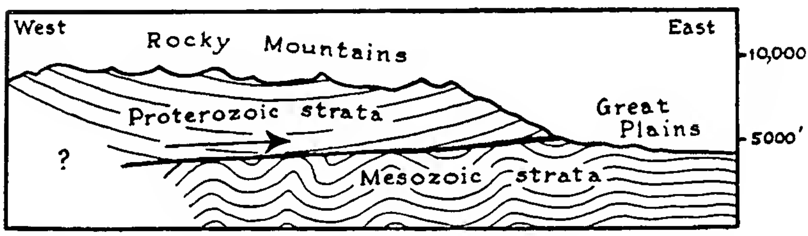



FIG. 299. Diagrammatic structure section showing how the great body of Proterozoic strata has been thrust-faulted from the west for miles over upon Late Mesozoic strata in Glacier National Park, Montana. The Mesozoic beds were folded by action of the over-riding block. Length of section, about 25 miles. Vertical scale, much exaggerated.

The original Rocky Mountains were greatly subdued by erosion by Middle Cenozoic time, and their existing altitude and main relief features are results of still later movements and erosion.

*Close of the Period in the East.* The whole eastern highland region extending from central Alabama through the Appalachian-Piedmont district, New York, and New England to the Gulf of St. Lawrence was subjected to erosion during most of the Mesozoic era. By Late Cretaceous time it was worn down to a condition varying from early old age to a peneplain. The most perfect peneplanation was in the northern Appalachians as, for example, from southern New York through Pennsylvania and the Virginias. Farther northward, however, over northeastern New York and northwestern New England, and also farther southward, as in western North Carolina, large masses of resistant rocks

stood out more or less prominently above the general level of the old-age surface.

According to D. W. Johnson, the old age (peneplain) surface was developed by the close of Early Cretaceous time after which a mantle of sediments was laid down over much of the thoroughly peneplaned portion (Fall Zone peneplain) in a Late Cretaceous sea which over-spread the region.

The Cretaceous period was closed in eastern North America by a disturbance which produced an upwarp of the vast old age (peneplain) surface (possibly in part veneered with Late Cretaceous deposits) with maximum uplift of many hundreds of feet. This upward movement was unaccompanied by real folding of the strata, the effect having been to produce a broad, irregular-shaped, elongate dome the main axis of which followed the general trend of the Appalachians and thence through northeastern New York and northwestern New England. The upward movement was, however, accompanied by the retreat of the sea from the Coastal Plain area (and also from much of the Appalachian area according to Johnson). This is proved by the widespread unconformity there between the Cretaceous and the Early Tertiary strata.

Another important effect of the general uplift was a renewal of erosion by streams, many courses of which followed down the slopes of the great upwarp.

**Cretaceous Climate.** The temperature of North America in Early Cretaceous time was generally somewhat below normal, probably because the continent stood higher than usual, particularly in the west where high, wide mountains, formed at the time of the Sierra Nevada Revolution, were still in their prime. Similar lower temperatures were prevalent in many other parts of the world as shown by the distribution of plants and animal fossils. Glaciers existed in eastern Australia.

As would be expected, because of the unusually extensive epeiric seas, the climate of Late Cretaceous time seems to have been generally mild, with some distinction of climatic zones. The fossil evidence (e.g. Late Cretaceous plants in Greenland) indicates mildness of climate even within the Arctic circle.

The general temperature again dropped at the close of the Cretaceous because of the great mountains formed at the time of the Rocky Mountain Revolution.

## CHAPTER XXII

## MESOZOIC LIFE

The physical revolution which closed the Paleozoic era was accompanied by one of the most profound changes in organisms in the earth's history, and hence we may expect the life of the Mesozoic to have been very notably different from that of preceding time. Some types of animals and various types of plants continued from the late Paleozoic, but the general aspect of Mesozoic life was distinctly more modern than that of the Paleozoic.

### Plants

**Seedless Plants.** *Thallophytes* were well represented during Mesozoic time, the lime-secreting *seaweeds* being especially common.

*Filicales* (*ferns*) continued to be important.

*Arthrophytes* (*"horsetail rushes"*) were common and varied. Except for their greater size they were much like existing forms.

*Lepidophytes* (*"club mosses"*) were greatly reduced even in Early Mesozoic time. The few lingering *sigillarians* disappeared with the Triassic, and the once important *lepidodendrons* were reduced to a very subordinate position much like those of today.

**Gymnosperms.** These seed-bearing, non-flowering plants dominated the plant world of the Mesozoic era until Late Cretaceous time just as the higher seedless plants dominated the Middle and Late Paleozoic plants. The important *pteridosperms* and *cordaites* became extinct in the Triassic.

*Ginkgos* (*"maidenhair trees"*), including various species, were common and widespread. One species of the ginkgo has survived to the present day. Among living trees, it is probably the world's most ancient species. The ginkgo evolved from cordaites or a closely related form in Late Paleozoic time.

*Cycads* and *conifers*, which made their advent in the Permian, were the most common of the larger plants during Mesozoic time.

The *Cycads* were palmlike in appearance, but they were lower order forms than the palms and distantly related to them. The short, stout trunks of the cycads were (and are) crowned with clusters of long, palmlike fronds (Fig. 300). They attained their zenith of development in the Jurassic, and their modified descendants still exist in parts of the world. Some of the fossil cycads found in Mesozoic strata show

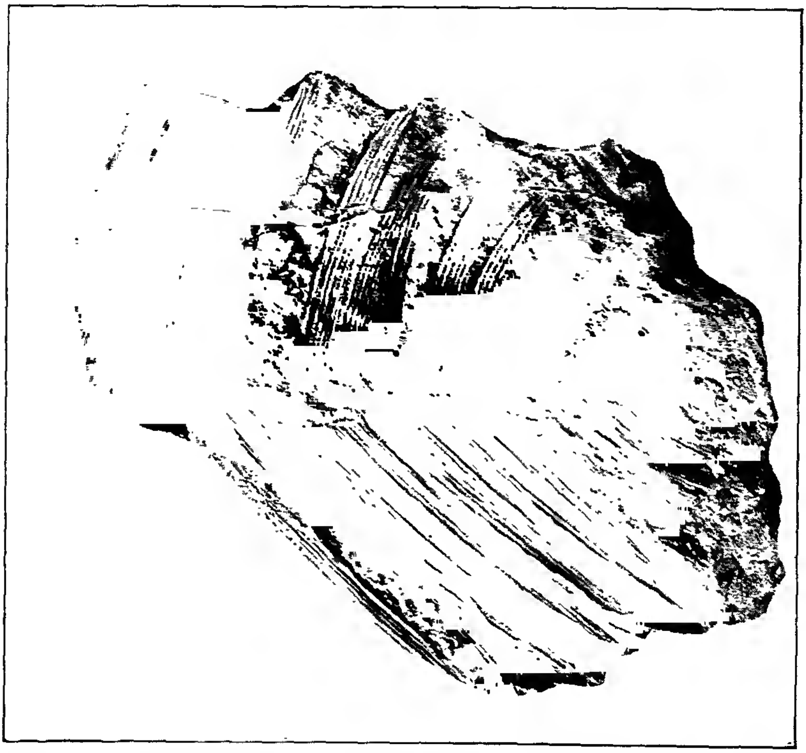


FIG. 300. Jurassic cycad leaves. (After Ward, U. S. Geological Survey, Monograph 48.)

a wonderful preservation of detailed structures of the plants. Cycads grew to be 40 to 60 feet high and several feet in diameter. From the standpoint of evolution, it is important to note that much evidence leads to the conclusion that the earlier Mesozoic cycads were the progenitors of the highest of all classes of plants—the angiosperms. The conifers, in marked contrast to this history, have not given rise to any higher group of plants.

The *conifers*, including pines, sequoias and many other types of evergreen trees, gradually became more varied, and more and more modern in aspect during Mesozoic time. *Sequoias*, represented by the present-day "Redwoods" and "Big trees" of California, began in Late Jurassic time, and they were varied and widespread in the Cretaceous. In various regions such as North Carolina, Virginia, and Arizona, trunks of fossil conifers reach diameters of 6 to 8 feet and lengths of 120 to 150 feet. The remarkably preserved petrified trees, found in such abundance and beauty of color in the Triassic strata of the Petrified Forest of Arizona, represent mainly conifers which grew to heights of fully 150 feet.

**Angiosperms.** Typical *angiosperms* are not definitely known to have existed before the Cretaceous, but there can be no possible doubt about their presence in Early Cretaceous time. By the close of the period the angiosperms had developed so phenomenally as to attain a position of supremacy among plants—a position which they have held ever since. The comparatively sudden appearance and remarkable development of the angiosperms "was one of the most important and far-reaching biologic events the world has known. . . . So far as we know, this flora appears to have had its origin in eastern or northeastern North America, in the Patapsco division of the Potomac series. Although the great majority of the plants found in association in these beds, both as regards species and individuals, still belonged to lower Mesozoic types, such as ferns, cycads, and conifers, we find ancient if not really ancestral angiosperms. . . . No sooner were they (angiosperms) fairly introduced than they multiplied with astonishing rapidity and in the . . . (Middle Cretaceous) they had become dominant, the ferns and cycads having mostly disappeared and the conifers having taken a subordinate position" (Knowlton). No present-day species existed, but, among the more modern genera were oaks, elms, magnolias, maples, figs, laurels, palms, grasses, etc.

## Invertebrate Animals

Among the tiny single-celled animals (*protozoans*), the foraminifers were exceedingly profuse during parts of Cretaceous time in clear sea waters which extended over the Gulf Coastal Plain area of the United States, southern England, much of France, and other areas. (Fig. 301.) Their shells helped to build up formations of chalk hundreds of feet thick and many miles in extent.

*Sponges* were very abundant and diversified. They are often beautifully preserved, even to the minutest details.

The modern types of *corals*, with six or eight partitions, began very late in the Paleozoic, and they were abundant and diversified throughout the Mesozoic. Like present-day corals they were tiny individuals, secreting carbonate of lime from sea water, and they nearly all grew in profusely branching colonies. The characteristic Paleozoic corals (with four partitions) became extinct in early Mesozoic time.

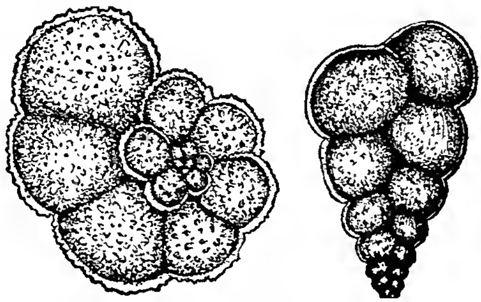


FIG. 301. Cretaceous foraminifers, greatly enlarged. (After Calvin, from Le Conte's "Geology," permission of D. Appleton and Company.)

*Echinoderms* underwent no really profound evolutionary change during the Mesozoic. All important subdivisions were well represented. The stalked forms ("stone lilies") took on a more modern aspect, and they were especially profuse and diversified during Jurassic time when single individuals are known to have had more than 600,000 segments made of carbonate of lime. The "sea-urchins" greatly increased in numbers, variety of forms, and often in size, during the Mesozoic era, and they were already distinctly modernized.

*Brachiopods*, which were so very abundant and diversified during Paleozoic time, greatly diminished during Mesozoic time until they occupied a very subordinate position in the animal world. Most of them had curved hinges.

Among the *mollusks*, both the pelecypods and the gastropods increased in abundance and variety of forms, and became more modern in appearance, during the Mesozoic. The oyster tribe and other closely related forms were prominent.

Chambered *cephalopods* were very numerous and diversified during Mesozoic time. The common and important straight-shelled Paleozoic forms with simple partitions became extinct early in the Mesozoic, but

simple-partitioned coiled forms remained common. An important evolutionary feature was the development of great complexity of shell structure during the Mesozoic era (Fig. 302). In many of the coiled forms the compartment partitions became so highly complicated as to be quite comparable to the sutures of human skull plates (Fig. 303). Several thousand species of such forms, known as *ammonites*, are known from the later Mesozoic strata which, in some localities, are literally filled with their fossil remains. Not only were they the most complex cham-

FIG. 302. A Triassic ceratite, *Ceratites trojanus*, with part of shell removed to show suture structure. (After J. P. Smith, slightly modified by accentuation of sutures.)

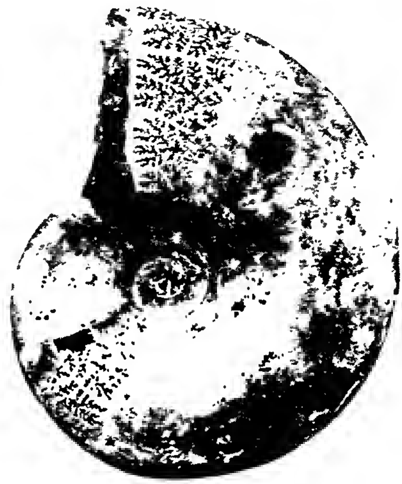


FIG. 303. A Cretaceous ammonite with part of outer shell removed to show the complicated suture or partition structure. Diameter of specimen, about 19 inches. (After Anderson and Hanna.)

bered cephalopods of all time, but also some of them were of great size. Some of the coils were several feet in diameter and would have been 30 or 40 feet long if straightened out.

During the Cretaceous many of the ammonites showed a remarkable tendency to assume strange forms. Some developed uncoiled shells; others spiral shapes; while still others were curved or actually straight. Thus, externally at least, there was a reversion to the early Paleozoic forms, but in all cases they retained their complicated suture or partition

structure. "These strange forms have been likened by Agassiz to death-contortions of the ammonite family; and such they really seem to be. From the point of view of evolution, it is natural to suppose that, under the gradually changing conditions which evidently prevailed in Cretaceous times, this vigorous Mesozoic type would be compelled to assume a great variety of forms, in the vain attempt to adapt itself to the new environment, and thus to escape its inevitable destiny. The curve of its rise, culmination, and decline reached its highest point just before it was destroyed. The wave of its evolution crested and broke into strange forms at the moment of its dissolution" (Le Conte). Very few if any ammonites crossed the line into the early Cenozoic, and such an abrupt termination of so abundant and diversified a group of animals has rarely been equaled in the history of the animal kingdom.

FIG. 304. A Jurassic belemnite, *Belemnoteuthis antiqua*. (Modified after Mantell.)

*Cephalopods* underwent another interesting evolutionary change during the Mesozoic era with the introduction and extensive development of the highest known types represented by the squids or "cuttlefishes" of the present day. The Mesozoic forms, called *belemnites*, had slender internal shells, but no chambered or external shells. Some of the Jurassic forms were two feet long (Fig. 304).

The *arthropods* underwent important changes in Mesozoic time. Among the crustaceans, the remarkable trilobites and eurypterids of the Paleozoic no longer existed, and in their place more highly organized and more modern forms, such as lobsters and crabs, became common. Great advances were made among the insects. During the Triassic the first beetles appeared, and these were distinctly higher order insects than any in the Paleozoic. During the Jurassic hundreds of species of insects are known to have existed. Simple forms were represented by beetles, while flies and still higher insects such as bees, moths, ants, and butterflies made their first appearance in the Jurassic. No such profound evolutionary change has occurred among the insects since those days. The insect life of the world was, therefore, remarkably modern in aspect thus far back in geological time.

## Vertebrate Animals

**Fishes.** A very important advance took place among the fishes with the introduction of the true bony fishes, known as *teleosts,* during Jurassic time. These comprise the most highly organized of all fishes, including such modern types as salmon, cod, and herring. They gradually evolved from the ganoids which latter continued to be the predominant fishes until Cretaceous time. Since that time the ganoids have dwindled almost to extinction, while the teleosts have become exceedingly profuse and diversified. The Jurassic teleosts were simple forms, not numerous, and frequently on the border between true ganoids and true teleosts. Cretaceous sharks, which were common and often large, have left an almost incredible number of fossil teeth.

**Amphibians.** Though somewhat diminished as compared with the later Paleozoic, Triassic amphibians were numerous and often notable for their great size. In general they were much like the late Paleozoic forms. *Mastodonsaurus* attained a length of 15 or 20 feet and had a skull 4 feet long. The Lower Triassic of Germany is particularly rich in fine fossil amphibians. By the close of the Triassic the amphibians had declined remarkably, so that among the land vertebrates, of which they were the ancestors, they never again assumed a position of importance. Comparatively few, relatively small forms, such as frogs, toads, and salamanders, represent this once great class of animals at the present time.

**Reptiles.** The Mesozoic era has been called the "Age of Reptiles," since those animals were at once the most characteristic and powerful creatures of the time. So far as known, the first true reptiles appeared in the Permian. During the Mesozoic they rose to great prominence, both in number of individuals and diversity and size of forms; reached their culmination in the midst of the era; and declined in a most remarkable manner toward the close of the era. During the Mesozoic the reptiles ruled all fields—sea, land, and air.

"The advance from the amphibian to the reptile was a long forward step in the evolution of the vertebrates. Yet in advancing from the amphibian to the reptile the evolution of the vertebrate was far from finished. The cold-blooded, clumsy and sluggish, small-brained and unintelligent reptile is as far inferior to the highest mammals, whose day was still to come, as it is superior to the amphibian and the fish" (W. H. Norton).

The following grouping of the more characteristic, extinct Mesozoic reptiles is not meant to be an exact scientific classification, but rather it is a simple arrangement for convenience of elementary discussion.

*Enaliosaurs.* There are many known types of these swimming rep-

FIG. 305. A remarkably preserved skeleton of a Jurassic ichthyosaur. It contains parts of several skeletons of unborn young. It is about 12 feet long. (Courtesy of the American Museum of Natural History.)

tiles, but only a few of the most typical and characteristic forms are chosen for description.

The *ichthyosaurs* were fishlike forms which ranged in length up to 25 or 30 feet (Fig. 305). They had stout bodies, very short necks, and

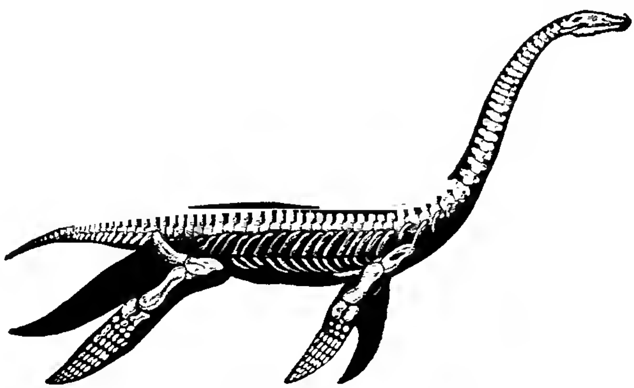


FIG. 306. A restored plesiosaur, *Plesiosaurus dolichodeirus,* of the enaliosaur division of Mesozoic reptiles. Maximum length 40 to 50 feet. (From Le Conte's "Geology," courtesy of D. Appleton and Company.)

very large heads. The head, sometimes 4 to 5 feet long, had an elongated snout in which as many as 200 large sharp teeth were set in grooves (not in sockets). Enormous eyes, sometimes over a foot in diameter, were protected by bony plates. A powerful tail with two

lobes set vertically had the vertebral column extending through the lower lobe. The four limbs were perfectly converted into swimming paddles, thus strongly suggesting that these, as well as other enaliosaurs, represent former land reptiles which adapted themselves to a water environment much like certain mammals of today, such as whales and dolphins. Ichthyosaurs ranged through the whole Mesozoic.

*Plesiosaurs* were less powerful forms than ichthyosaurs, though they were usually longer, some having attained a maximum length of 40 to 50 feet (Fig. 306). A stout body, long, slender neck, small head, short

FIG. 307. A mosasaur, *Tylosaurus dyspelor,* of the enaliosaur division of Mesozoic reptiles. Maximum length about 75 feet. Restoration by C. R. Knight under the direction of H. F. Osborn. (Courtesy of the American Museum of Natural History, from Scott's "Geology," by permission of the Macmillan Company.)

tail, and four powerful paddles were characteristic features. Sharp teeth were set in sockets (not grooves) in the jaw. Plesiosaurs ranged through the whole Mesozoic.

*Mosasaurs* were actual sea-serpents or carnivorous marine reptiles which often reached a length of from 40 to 75 feet (Fig. 307). Though now wholly extinct, they were closely related to snakes and lizards in structure. The four limbs were converted into short, stout, swimming paddles, and their jaws were set with sharp teeth. Mosasaurs existed during the latter portion only of the Mesozoic.

*Dinosaurs.* These walking reptiles comprised a great variety of forms as regards both shape and size. Only five of the more common and characteristic types have been selected for description. Like most other reptiles, the dinosaurs laid eggs, fossilized specimens of which have been found.

The *sauropods* were the largest of all Mesozoic reptiles, and in fact they included the largest animals which ever trod the earth. Well-preserved specimens are known whose lengths are from 75 to 90 feet, and recently one has been discovered in Utah which it is thought will, when

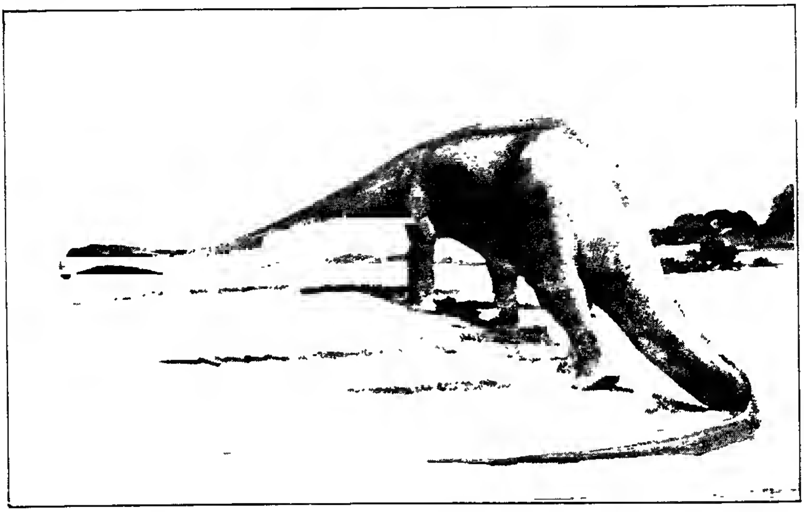


FIG. 308. The hugest of all known dinosaurs, a sauropod, *Diplodocus.* A mounted skeleton in the Carnegie Museum of Pittsburgh measures 87 feet long. Restored by C. R. Knight under the direction of H. F. Osborn. (Courtesy of the American Museum of Natural History.)

mounted, show a length of over 100 feet. It has been estimated that one of these large brutes must have weighed about 40 tons. Note the extremely long neck and tail, very small head, and strong bones of the four great legs. Thigh bones 7 feet long are known. They were five-toed and plantigrade, and doubtless walked with body well above ground (Fig. 308). All were plant-eaters and provided with grinding teeth. Sauropods ranged through all the Mesozoic except the Triassic.

The *stegosaurs* are so named because of the double row of great bony plates on the back of each of these most remarkable brutes (Fig. 309) which attained a maximum length of 30 to 40 feet. The long,

powerful tail had several pairs of long spines toward the end instead of plates. All were plant-eaters. The brains of all dinosaurs were almost incredibly small, even as compared with modern reptiles, and this was notably true of stegosaurs. Stegosaurs existed through all of the Mesozoic except the Triassic.

*Triceratops* was another strange-looking creature, so named because of its three horns—two of great size just back of the eyes and a smaller one on the nose (see Fig. 310). The enormous flattened skull had a sharp beak in front. The skull extended backward into an immense

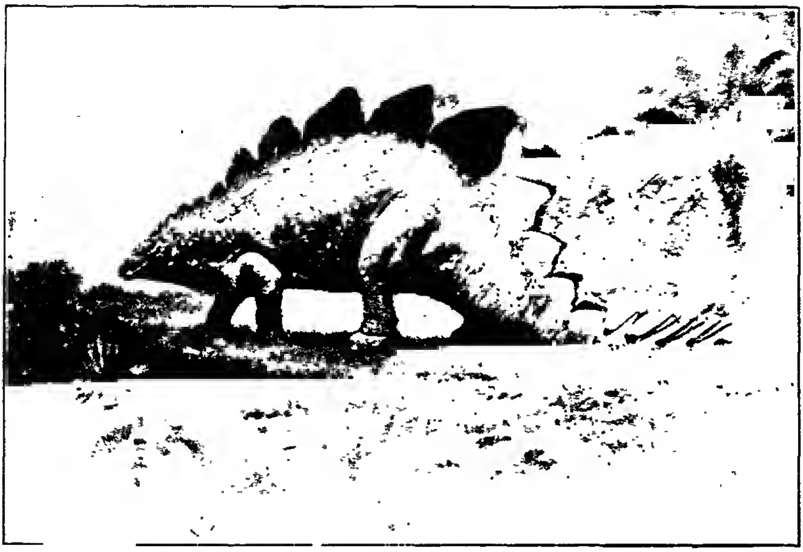


FIG. 309. A stegosaur, an armored dinosaur. Maximum length 30 to 40 feet. Restored by C. R. Knight. (By permission of F. A. Lucas and Doubleday, Page and Company, and courtesy of Henry Holt and Company.)

hood or capelike structure. According to Marsh they (triceratops) had the largest heads and smallest brains of the reptiles, and hence they must have been exceedingly stupid. Skulls 6 or 8 feet long have been found. The four legs and the tail were massive and powerful. This creature attained a length of fully 25 feet, and it had a bulk about twice that of an elephant. It was a plant-eater and probably not as ferocious as it looked. Good specimens have been found in the western interior of the United States. Triceratops existed only during the Cretaceous period.

*Theropods* were carnivorous dinosaurs, as proved by their numerous sharp teeth set in comparatively large heads (see Fig. 311). They were bipedal, that is they walked on two legs, the front limbs having been very small and used only for grasping. The toes were armed with sharp claws. Theropods varied in length from 4 to over 40 feet, and though much smaller than many other dinosaurs, they were probably the most ferocious of all and more than likely preyed upon the much larger plant-eaters. A mounted skeleton of one of these creatures, called Tyrannosaurus, in the American Museum of Natural History is 47

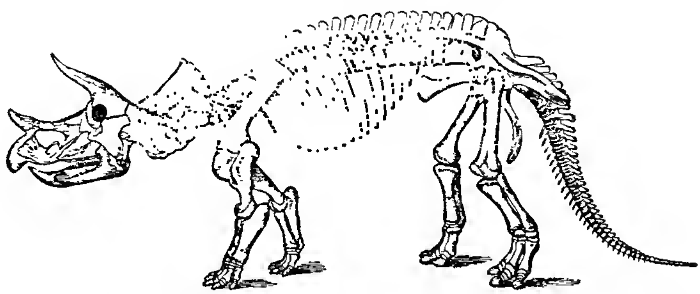


FIG. 310. A triceratops, *Triceratops prorsus*, of the dinosaur division of Mesozoic reptiles. Maximum length 25 feet. (Skeleton restored by Marsh.)

feet long. It represents the greatest known flesh-eating land animal of all time. The theropods lived through the whole Mesozoic.

*Ornithopods* were in general appearance much like the theropods, but they were certainly plant-eaters, as shown by the tooth structure. They were bipedal, the hind limbs having only three functional toes, giving a sort of birdlike track. The largest of these creatures measured 30 feet in length, and when walking they must have stood 15 or 20 feet high. Ornithopods ranged through all the Mesozoic except the Triassic.

*Pterosaurs.* These were actual "flying-dragons" in Mesozoic time. They varied greatly in size from about that of a sparrow to others with a spread of wing of 25 feet, which is about twice that of any modern bird. Not only did they include the largest creatures which ever flew but, on account of their hollow bones, their skeletons were wonderfully light. One finger of each front limb was enormously lengthened to support the flying membrane, as shown in Fig. 313. The other fingers were armed with sharp claws.

The earlier Mesozoic forms were supplied with sharp teeth, while the Cretaceous forms were mostly toothless.

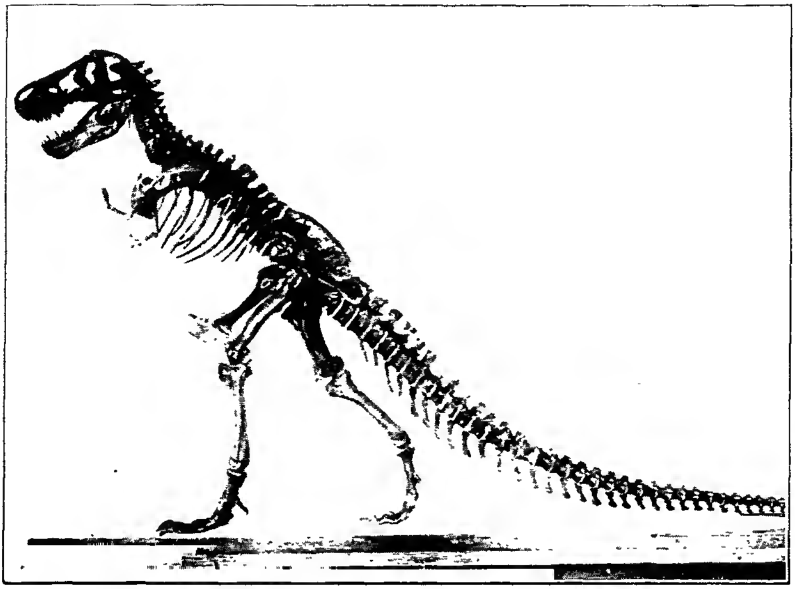


FIG. 311. Skeleton of a great two-legged theropod dinosaur (*Tyrannosaurus*) from the Cretaceous strata of Montana. Tyrannosaurus, nearly 50 feet long, was the greatest carnivorous land animal of all known time. (Courtesy of the American Museum of Natural History.)

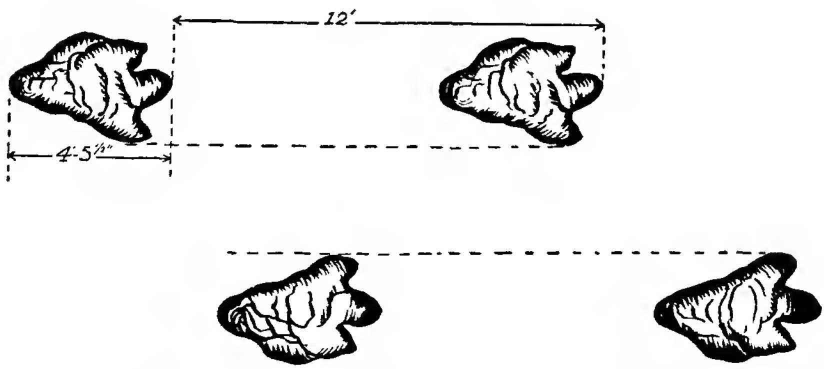



FIG. 312. A sketch of footprints, each over 4 feet long, left by a great two-legged dinosaur with a stride of 12 feet. Found in coal-bearing Cretaceous strata at Standardville, Utah. (After C. N. Strevell.)

*Modern Representatives.* Though overwhelmed by the reptiles above described and of less peculiar interest because they represent

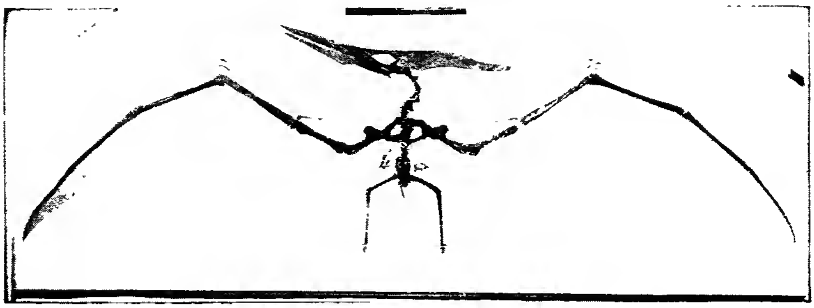


FIG. 313. Skeleton of a Cretaceous pterosaur known as *Pteranodon.* This great flying reptile, with a wing-spread of nearly 25 feet, was the largest of all known flying creatures. Note the impressions of the membranous wings. (Courtesy of the American Museum of Natural History.)

groups still living, certain other Mesozoic reptiles deserve brief mention.

*Turtles* date back at least to the Middle Triassic, and even those

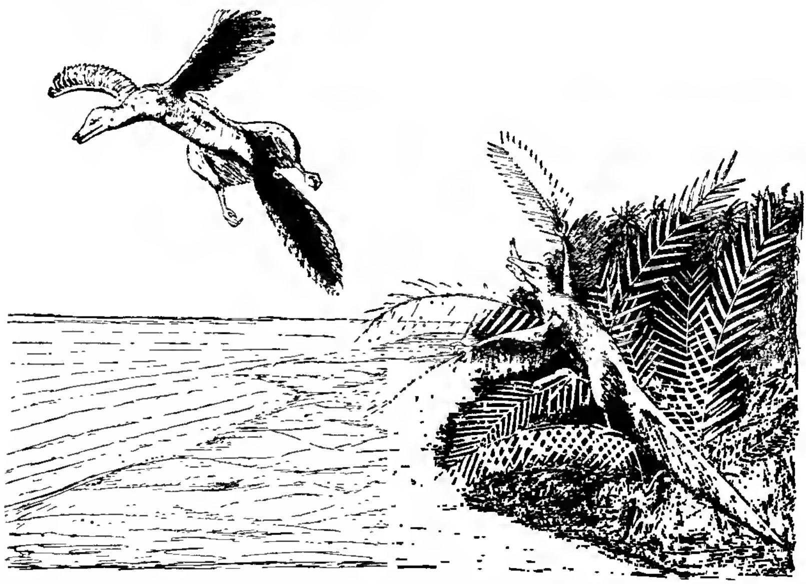


FIG. 314. Restoration of the earliest known bird (*Archeopteryx macrura*) from the Jurassic. (After E. W. Berry, from his textbook of "Paleontology.")

very early forms clearly showed the familiar structure which easily separates them from other reptiles.

*Lizards* are known even from the Triassic, and, though they ranged through the Mesozoic, they were always small and comparatively rare.

*Crocodiles* made their first appearance in the Jurassic, and some were marine forms. In appearance they resembled the modern gavial of India, particularly as regards the long, slender snout. Crocodiles were numerous from the Jurassic to the end of the Mesozoic.

*Snakes* are not known to have appeared till late in the Cretaceous, and those early forms were small and comparatively rare.

**Birds.** These constitute next to the highest class of all vertebrate animals. They and the still higher mammals are the only warm-blooded creatures. A very important feature, from the standpoint of evolution, was the introduction of the feathered creatures during the Jurassic period. The oldest known bird (Fig. 314) had certain distinct reptilian characteristics which make it practically certain that it was evolved from certain types of two-legged Mesozoic reptiles, and not as might be presumed, from the flying reptiles. Two specimens of the primitive Jurassic bird are so remarkably fossilized that practically the complete skeletons and nearly perfect impressions of the feathers have been preserved in the rock. The creature had, in addition to its true bird features of feathers, feet, brain, beak, and limb bones, reptile features of long vertebrated tail, teeth set in sockets, and long claws on the wings. The creature was aboout the size of a crow.

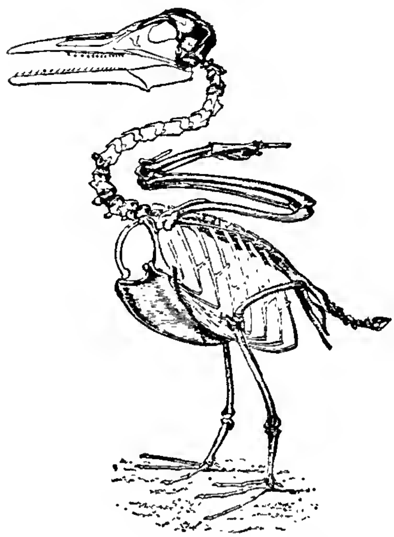


FIG. 315. A Cretaceous toothed bird, *Ichthyornis victor*. Height, about 8 inches. (After Marsh.)

Notable evolutionary progress was made among the birds during Cretaceous time. They were distinctly more advanced and modern in appearance than were those of the Jurassic (Fig. 315). Thus the long vertebrated tail of the earlier forms had become greatly shortened, but they still retained an important primitive characteristic, namely, the possession of teeth. They had much smaller brain cavities than modern

birds, and many of them were powerful fliers. Some grew to be five or six feet long.

**Mammals.** A very important event in the history of animal life was the first appearance of *mammals* in the Early Mesozoic. Mammals comprise the highest class of all animals. They are characterized by suckling their young and having hair on their bodies. For convenience of discussion we shall consider them in three categories as follows: (1) *monotremes* or egg-laying forms, such as the modern spiny ant-eater; (2) *marsupials* (e.g. opossum and kangaroo) or those giving birth to imperfectly formed young which are carried for some time in a pouch (marsupium) by the mother; and (3) *placentals* (e.g. dog, horse, and man) or those giving birth to well-formed young which, in a prenatal condition, are attached to the mother by the placentum.

Monotremes made their first appearance in the Triassic; marsupials in the Jurassic; and primitive, low-order placentals in the Late Cretaceous.

Throughout the Mesozoic era the mammals occupied a very subordinate position among animals. They seem to have been almost completely overshadowed by the hordes of reptiles.

Mammals, like the birds, evolved from certain types of reptiles. various transitional forms between reptiles and mammals being known from the fossil record.

# CHAPTER XXIII

## CENOZOIC ROCKS AND HISTORY

### (EXCLUDING THE ICE AGE)

### General Statement

The Cenozoic era not only is the last one of geologic time, but also it is the shortest, with an estimated duration of 50 to 60 million years. During this short era the relief features of the earth have been revolutionized and brought to their present-day condition. It is doubtful if a single landscape feature of today was in existence as such prior to the opening of the era. Thus the face of North America has been completely made over in Cenozoic time. All mountains, hills, valleys, canyons, plateaus, and plains have assumed their present-day sizes and shapes; all existing lakes, shorelines, and waterfalls have been formed; the modern climatic zones have developed; and plants and animals (particularly mammals) have evolved to their modern condition.

Following are the subdivisions of the Cenozoic era now commonly recognized throughout the world:

| | | |
|---|---|---|
| CENOZOIC ERA | Quaternary period | 2. Recent (post-Glacial) epoch |
| | | 1. Pleistocene (Glacial) epoch |
| | Tertiary period | 4. Pliocene epoch |
| | | 3. Miocene epoch |
| | | 2. Oligocene epoch |
| | | 1. Eocene epoch (Paleocene) |

### Cenozoic Rocks

Tertiary strata appear at the surface in North America over the areas indicated on the accompanying map (Fig. 316). The important regions are the Atlantic and Gulf Coastal Plains, the West Indies, the Great Plains, and the great western (Cordilleran) region. The discontinuity of the large and small areas of the two coastal plains is because of the fact that later (Quaternary) deposits rest upon and conceal the Tertiary strata in places. Tertiary strata constitute a vast area

of surface rocks in the Great Plains of the United States and southern Canada. In the western interior the numerous disconnected areas represent chiefly deposition in separate basins or remnants of erosion of once larger areas. On the Pacific Coast Tertiary strata appear mostly as comparatively small, narrow belts because only the eroded edges of the usually upturned and folded rocks are visible in the mountains. Such

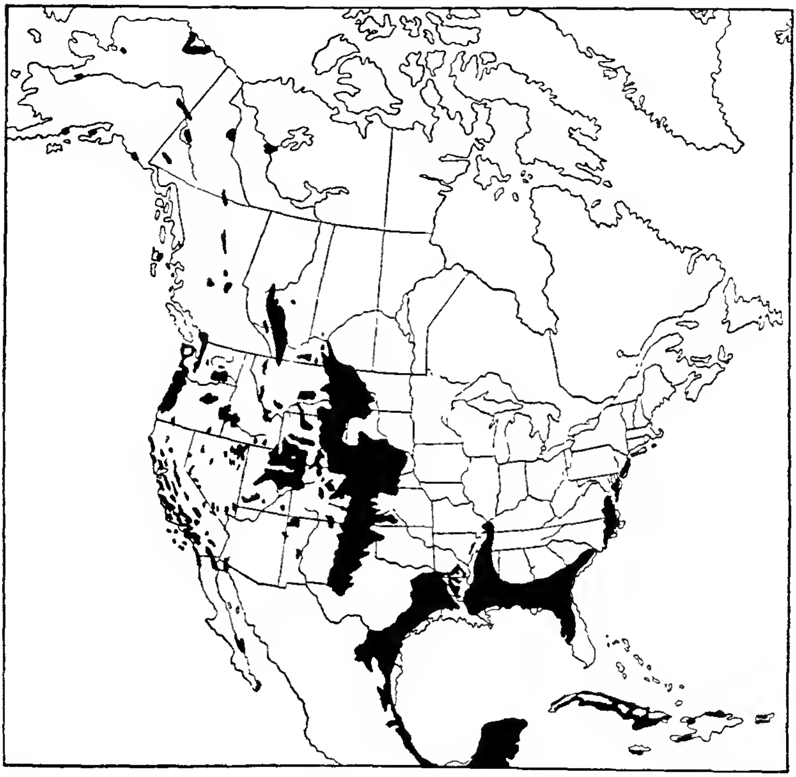


FIG. 316. Map showing the surface distribution (areas of outcrops) of Tertiary strata in North America. Tertiary volcanic rocks are separately shown on another map (Fig. 333).

strata are in reality much more extensively developed than the surface areas seem to indicate.

There is no evidence that Tertiary strata ever were deposited over any other parts of the continent than those above mentioned.

Quaternary sediments, in the form of surface and near-surface (surficial) deposits, showing little or no consolidation, are widely scattered

over the continent. The only marine Quaternary beds occur near the coasts, as on the outer sides of the Atlantic and Gulf Coastal Plains, and along the Pacific margin of the continent. Non-marine deposits, such as glacial, stream, lake, and wind-blown materials are very common.

The Tertiary strata of the Atlantic Coastal Plain are mostly unconsolidated formations of sands, gravels, clays, and marls. Almost all of these formations are of marine origin and they are usually very fossiliferous. In the Gulf Coastal Plain both marine and non-marine deposits

FIG. 317. The Green River formation of Eocene age as seen near Green River City, Wyoming. The well-bedded, nearly horizontal shales were laid down in a great fresh-water lake. (Photo by courtesy of the Union Pacific Railroad.)

occur, with the former predominant. The older formations have usually been hardened into sandstones, shales, and limestones, with much lignitic coal in places, while the middle and later Tertiary strata are unconsolidated sands, clays, and marls. Unconsolidated Quaternary deposits, consisting of both non-marine sediments and marine terrace and beach materials, conceal the Coastal Plain strata in many places, especially near the coast. The Coastal Plain strata are almost entirely free from folds and faults, but some broad, very gentle warps do occur. The practically unconsolidated Tertiary strata everywhere dip gently toward

the sea. For this reason successively older formations are encountered in passing inland from the coast (Fig. 325).

The western interior-Great Plains region includes the Great Plains (lying east of the Rocky Mountains), the Rocky Mountains, the Colorado Plateau, the Basin and Range Province, and the Columbia Plateau (see Fig. 1). Cenozoic strata, all of continental origin, occur in small and large areas in many places throughout this great region (Fig. 316). They comprise various kinds of materials such as lake, river, alluvial-fan, and wind-blown sediments. Beds of imperfect (lignitic) coal also

FIG. 318. Soft volcanic tuff and shaly sandstone of Late Tertiary age in Red Rock Canyon north of Mojave, California. The cliff, about 200 feet high, is remarkably sculptured by rain-wash.

occur in various places. Eocene lake beds are very extensive, especially in Utah and Wyoming (Fig. 317). Igneous rocks of Cenozoic age are also of very great extent and importance in the western interior region (Fig. 333). Most extensive by far are the Tertiary volcanic rocks, but small bodies of intrusive rocks such as batholiths, laccoliths, and dikes also are known. Some Quaternary volcanic rocks occur here and there.

The structure of the Cenozoic strata of the Great Plains is simple. There is very little folding or faulting, and the various formations nearly everywhere show a gentle eastward dip. In the Rocky Moun-

tains the Cenozoic rocks, particularly the older formations, have often been disturbed by faulting and some tilting, but in many areas (often extensive) they still lie in their original horizontal positions. Between the Rocky Mountains and the Sierra-Cascade Mountains, Cenozoic rocks—both sedimentary and volcanic—have often been locally disturbed by some folding, as in the Columbia Plateau; or by tilting; or often by faulting, as in the Basin and Range Province (Fig. 330).

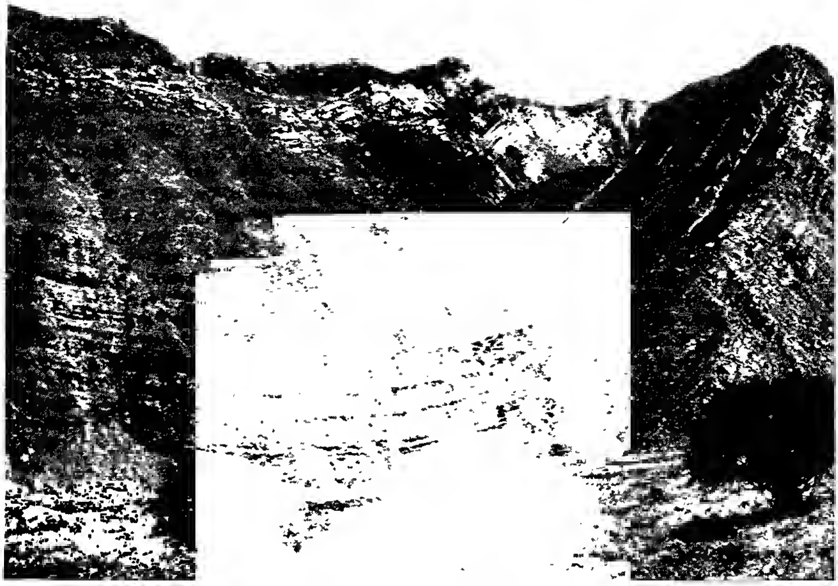


FIG. 319. Part of a syncline showing earlier Tertiary marine strata. Prominently outcropping beds toward the lower and right sides of the syncline are Upper Eocene; the boldly outcropping beds (lighter colored) next above are Oligocene; and at the top there is some Miocene. San Emigdio Canyon, south of Bakersfield, California. (After R. Anderson, U. S. Geological Survey, Bul. 471.)

Pacific Coast Tertiary marine strata, together with some brackish, fresh-water, and continental deposits, are extensively developed west of the Sierra Nevada and Cascades, and along the southern coast of Alaska. They are wonderfully developed in California, especially the Eocene and the Miocene.

The Pacific Coast Tertiary strata are very largely sandstones, shales, conglomerates, often with much diatomaceous shale. These are usually much folded and faulted, particularly in the Coast Range Mountains.

Miocene strata in California reach a thickness of 15,000 to 20,000 feet, one formation alone being 7000 feet thick west of Los Angeles. Some marine Quaternary strata occur on the Pacific Coast, especially those of the Los Angeles-Ventura region in southern California. Quaternary continental deposits of stream, lake, and alluvial-fan origin are more widespread than the marine deposits on the Pacific Coast. These generally unconsolidated materials usually occupy valleys between the mountains and ridges, as for example on a grand scale in the Great Valley of California. Cenozoic volcanic and dike rocks are found in

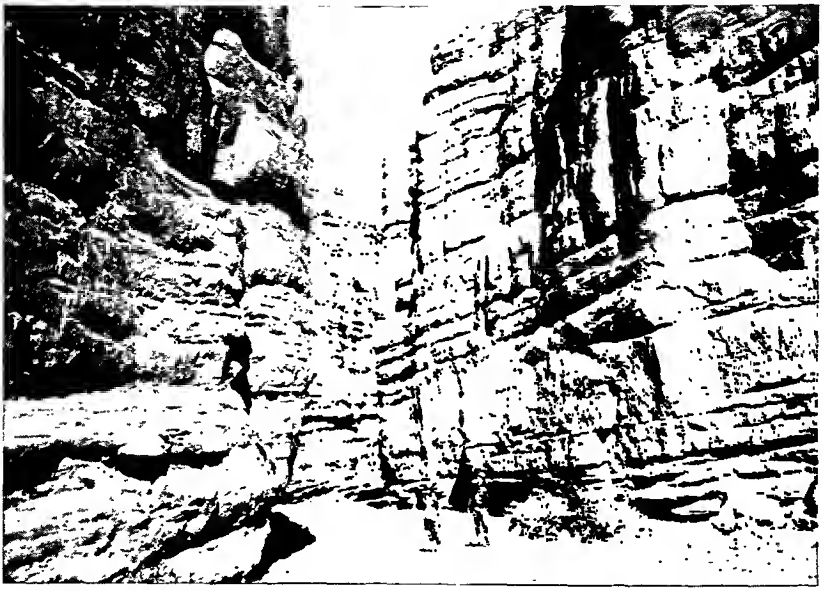


FIG. 320. Nearly horizontal beds of non-marine, red sandstone of Late Tertiary age. Painted Canyon, east of Mecca, California.

most parts of the Pacific Coast. Probably every epoch of the Cenozoic is represented by them. Particularly important are the great Tertiary volcanic formations of the Cascade Mountains and the northern Sierra Nevada Mountains; western Washington and Oregon; and the Coast Range of California.

Maximum thicknesses of the Tertiary system (not including volcanic rocks) are: Atlantic Coastal Plain, 1000 feet; Gulf Coastal Plain, 3000 to 5000 feet; western interior-Great Plains, 5000 to 10,000 feet; and Pacific Coast, 20,000 to 40,000 feet. Volcanic rocks of western North America are often thousands of feet thick.

## Cenozoic History

**Cenozoic Seas.** During Paleozoic time epeiric seas spread over, and disappeared from, extensive parts of North America many times. Such seas were far less common in the Mesozoic era, the most important having been the great western sea which cut the continent in two in

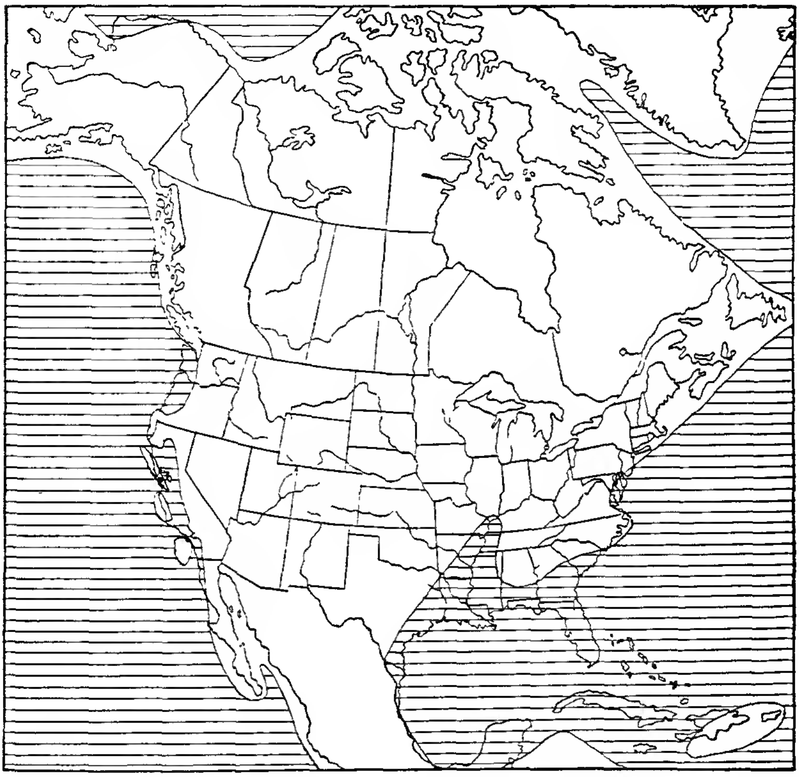


Fig. 321. Generalized paleogeographic map showing sea and land relations in North America during Eocene time. White areas, land; ruled areas, sea. Principal data (modified) after B. Willis, C. Schuchert, and F. Tolman.

Late Cretaceous time. During the Tertiary period none of the still more restricted epeiric seas ever cut across the continent, or even extended very far into it. As a matter of fact, sea water spread over less of the continent during the Tertiary period than at the present time. The accompanying maps show the extent of the seas during each of the four Tertiary epochs in North America.

Early in the Quaternary period, the marginal seas were of very slight extent—much less even than in the Pliocene. During most of the period, North America seems to have been both broader and generally higher, relative to sea level, than it is today, with land extending out over the continental shelf areas. The remarkable submarine canyons now occurring on both sides of the continent were then quite likely

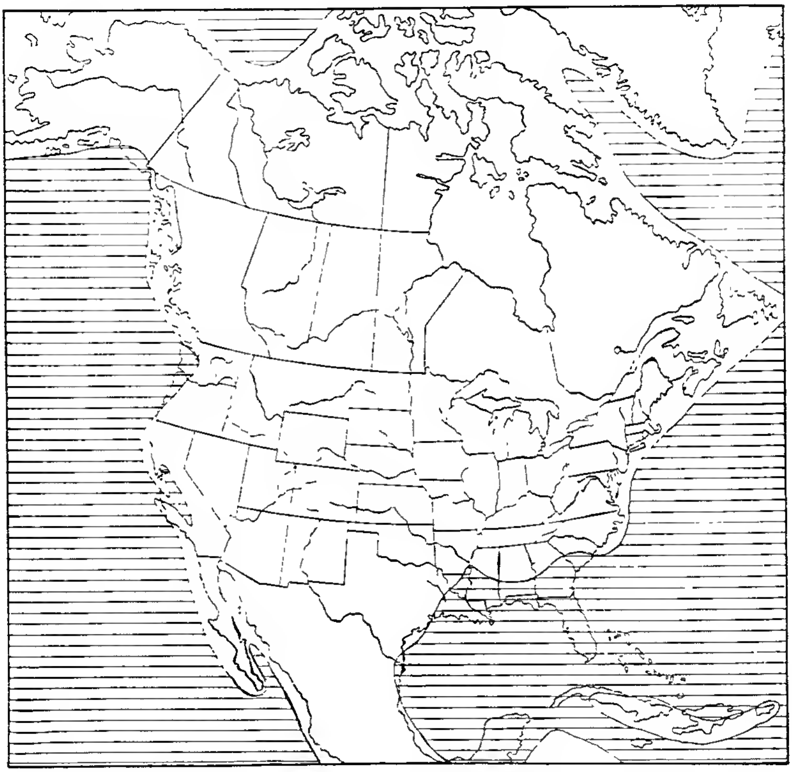


FIG. 322. Generalized paleogeographic map showing sea and land relations in North America during Oligocene time. White areas, land; ruled areas, sea. Principal data (modified) after B. Willis, C. Schuchert, and R. Reed.

cut by rivers on the margins of the higher and more extensive continent. At the same time the level of the sea no doubt stood several hundred feet lower than now because so much water from the sea was transferred to the lands in the form of the great ice sheets which covered many millions of square miles of land.

In Late Quaternary time, possibly because of the great weight of

the glaciers, the continent became notably depressed. The continental-shelf areas, with their newly cut canyons, became submerged, and sea water also spread over parts of the continent much more extensively than at any other time during the Cenozoic era. Hudson Bay was then formed; much of the Arctic Islands region was submerged; the Gulf of St. Lawrence was formed; the coasts of southern Alaska, British

FIG. 323. Generalized paleogeographic map showing the relations of sea and land in North America during later Miocene time. White areas, land; ruled areas, sea. Principal data (modified) after B. Willis and R. Reed.

Columbia, and southern California were then partly submerged, in each case leaving off-shore islands, many of which have existed to the present time. San Francisco Bay and Puget Sound were then formed by subsidence.

During still later (Recent) time, much of North America, especially its northeastern one-quarter, has been partially and unequally re-elevated,

but it is still below its earlier Quaternary general height, relative to sea level.

**Eastern North America.** *Atlantic Coastal Plain.* During most of Eocene and Oligocene times, much of the southern Atlantic Coastal Plain and Florida were occupied by sea water (Figs. 321, 322), while the middle part of the coastal region was land. Part of the northern

FIG. 324. Generalized paleogeographic map showing the relations of sea and land in North America during Pliocene time. White areas, land; ruled areas, sea. Principal data (modified) after C. Schuchert and R. Reed.

Atlantic Coastal Plain was sea covered in the Eocene, but it was all land in the Oligocene.

Much of the Atlantic Coastal Plain region and Florida were submerged during most of Miocene time (Fig. 323).

During the Pliocene epoch only parts of the seaward edge of the Atlantic Coastal Plain and the eastern one-half of Florida were sub-

merged, the Late Pliocene being represented by marine-terrace deposits now lying a few hundred feet above sea level.

During the Quaternary period a series of five or six unconsolidated marine deposits were laid down on the outer part of the coastal plain area. Each of these is represented topographically by a more or less distinct marine terrace, the oldest being at the highest level.

The modern shoreline has developed in detail during the present (Recent) epoch.

*Gulf Coastal Plain.* During Eocene time extensive sedimentation

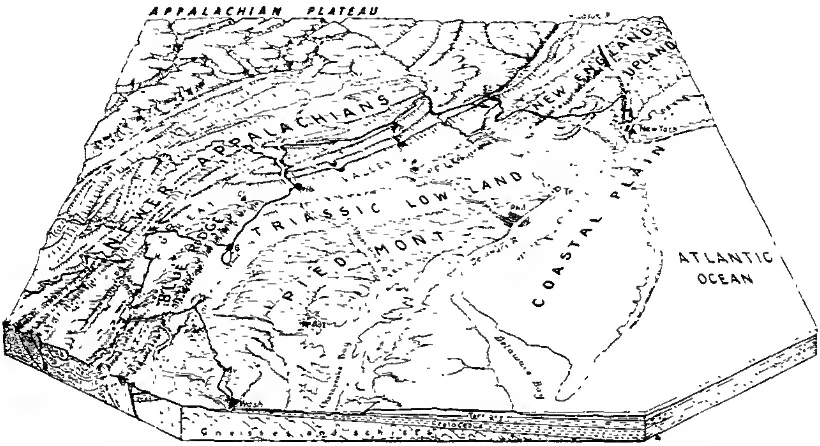



FIG. 325. Block diagram showing the topographic features and relations of the northern Appalachian and northern Atlantic Coastal Plain regions, and the structures of the underlying rocks. The gneisses and schists are pre-Paleozoic in age. Note the gently dipping Cretaceous and Tertiary strata underlying the Coastal Plain. Also note how the superimposed Potomac, Susquehanna, Delaware, and Hudson Rivers cut across the ridges and the geologic structures. The heavy line indicates the route of a geological excursion. (From International Geological Congress Guidebook No. 7. Drawn by E. J. Raiz.)

took place over much of the Gulf Coastal Plain region (Fig. 321). An embayment of the Gulf extended northward in the Mississippi River region, as far as Illinois much as it did in the Late Cretaceous. An unconformity between the Cretaceous and Eocene clearly shows that there was a transgression of the Eocene sea over the area. Marine conditions in this embayment were, however, more or less interrupted by considerable development of non-marine deposits such as lignite beds.

Oligocene conditions were a good deal like those of the Eocene, but the Mississippi embayment was much less pronounced and very little of the coast of Texas was then submerged (Fig. 322).

During Miocene time the Mississippi embayment was gone as such, but sea water spread over the southern part of the Gulf Coast most of the time (Fig. 323).

In the Pliocene epoch only that part of the Gulf Coast margin from Mississippi westward was submerged, and the eastern Gulf Coast received non-marine deposits (Fig. 324).

Some marine sediments were laid down along the margin of the Gulf Coast during Quaternary time, and late in the period (Recent epoch) the present shoreline became established.

*Eastern Highland Region.* This region includes the whole highland area extending from central Alabama through the Appalachian district, New York, and New England to the Gulf of St. Lawrence. Mention has already been made of the facts that the whole region, from the Gulf of St. Lawrence to central Alabama, was, by Late Cretaceous time, worn down to an old age-peneplain surface (Fall Zone peneplain); that the old surface was in part covered with alluvial deposits and in part probably with Late Cretaceous marine deposits; and that this surface was notably upwarped or arched at the close of the Cretaceous. Many streams flowed down the slopes of the great upwarp, first cutting channels through the thin mantle of alluvial and (or) marine deposits, and then into the underlying rocks, irrespective of the kinds and structures of the underlying rocks, thus causing them to become superimposed streams. Important among such streams which have persisted to the present day are the Susquehanna, Delaware, Potomac, and Hudson Rivers, all of which follow courses out of harmony with the structures of the regions through which they flow.

By about Middle Tertiary time, the eastern highland region was again largely reduced to an old age-peneplain surface.

In later Tertiary time, the old age-peneplain surface was upwarped unevenly in amounts usually ranging from a few hundred feet to a few thousand feet. This was an event of prime importance in the Cenozoic history of the eastern United States because it was the first step in the development of most of the existing relief features of the whole eastern highland region, these features having been produced by dissection of that upraised surface. The dissection was very largely the work of erosion by streams, but more locally (e.g. the southeastern Adirondack region) faulting has produced notable effects. All the valleys, great and small, such as the Champlain, Connecticut, Mohawk, Hudson, and Great Lakes Valleys, and the numerous valleys in the Appalachian region, have been produced since the uplift of the old

worn-down Middle Tertiary surface. Many remnants of the peneplain surface still remain. In the southern Appalachians (e.g. the Great Smoky Mountains), New England, and the Adirondack Mountains of New York, parts of the regions are composed of very resistant plutonic and metamorphic rocks, and hence they were not reduced to a stage beyond that of early old age or late maturity (Fig. 326).

The commonly occurring, deep, broad-bottomed, stream-cut valleys, in the area under discussion, show that many of the streams had reached graded, or nearly graded, condition even by the close of the Tertiary (Fig. 326). In the northern Appalachian district, at least, we have evidence to show that after the streams had reached grade there was an appreciable renewed uplift of the land which again revived the

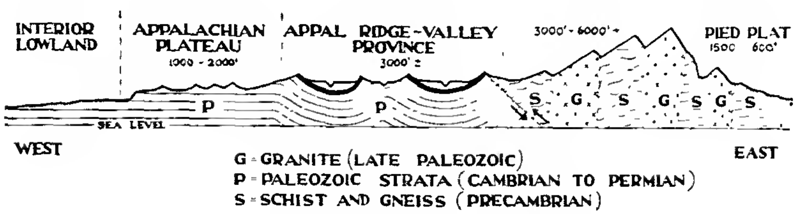



FIG. 326. This highly generalized profile and structure section shows the topographic and geologic relations of the various provinces of the southern Appalachian region. The highest part represents the Great Smoky Mountains of the Blue Ridge Province. These mountains were not peneplaned by Middle Tertiary time. The vertical scale is greatly exaggerated.

activity of the streams. Thus the broad Hudson Valley, with minor hills rising above its surface, was produced when the Hudson was well along toward a graded condition and then, as a result of this Late Tertiary uplift of the land, the present narrow and fairly deep inner valley of the Hudson was formed. The Hudson did not reach grade in this inner valley, its work having been interrupted by both the subsidence of the land and the spreading of the great ice sheet over the region. This inner valley of the Hudson has been traced for fully 100 miles eastward beyond the mouth of the present river. The Coast and Geodetic Survey has made a detailed map of the ocean bottom near New York City, and the submerged valley of the Hudson River is clearly shown as a distinct trench cut into the continental shelf. Even in the Hudson Valley above New York City, the narrow inner valley has a depth of hundreds of feet and is mostly submerged below tide water. Without question, this submerged Hudson Valley was cut

when the region was land, and thus we have positive proof that, late in the Tertiary and possibly extending into the Early Quaternary, the region of southeastern New York was notably higher than it is today. Conservative estimates place the amount of elevation greater then than now at not less than 1000 feet because the end of the Hudson channel is submerged fully that much. The coast was then at what is now the edge of the continental shelf or platform about 100 miles east of the present coast line. That this greater altitude was before the Ice Age is proved by the fact that the inner Hudson Valley now contains much glacial débris. By similar reasoning, based upon the drowned valleys of the Maine Coast and the lower St. Lawrence, we know that all of the middle Atlantic seaboard region, at least, was notably higher in Late Tertiary time than now.

During Pleistocene time, the northern part of the Eastern Highland Region, including New York and New England, subsided (possibly because of the weight of the glacial ice upon it) so that by the close of the epoch, and shortly after, the land was relatively lower even than it is today. It was during this time of subsidence (sometimes called the Champlain epoch) that the lower Hudson and St. Lawrence Valleys were submerged and the seacoast was transferred to more nearly its present position. But the land being even lower than now, the lowlands of Long Island and in the vicinity of New York City were under water and a narrow arm of the sea extended through the Hudson and Champlain Valleys to join a broad arm of the sea which reached up the St. Lawrence Valley and possibly even into the Ontario Basin. This so-called Champlain Sea existed at the time of the Nipissing stage of the Great Lakes described beyond (Fig. 347). Champlain Sea beaches, containing marine shells and the bones of walruses and whales, have been found at altitudes of about 500 feet near the southern end of Lake Champlain, 750 feet at its northern end, and 500 to 700 feet or more in the St. Lawrence Valley. The deposits of this age are about 50 feet above sea level near New York City, and at Albany a little over 300 feet. The altitudes of these so-called raised beaches show how much lower the land was during the time of greatest submergence, and that the subsidence was most toward the north. That this greatest submergence occurred after the close of the Ice Age in this region is proved by the fact that the now raised beaches and marine deposits rest upon the latest Glacial drift.

The most recent movement of the earth's crust in the New York-New England region was the very gradual elevation which expelled the

Champlain Sea and left the land at its present height. The altitudes of the raised Champlain beaches show that the greatest uplift was on the north. Up-tilting of various post-Glacial (Recent) lake deposits, at the rate of several feet per mile northward, prove the same thing.

*Interior Lowland.* The great Interior Lowland Province, in the midst of the continent (Fig. 1), has been above sea level and subjected to erosion for a long time—the part from eastern Oklahoma and Wisconsin to New York since the close of the Paleozoic, and the western border and northwestern parts since the close of the Mesozoic era. A general, though moderate, uplift of the region took place in Early Cenozoic time. By the Late Tertiary the region was worn down to a condition varying from old age to a peneplain. This old, low-lying surface was rejuvenated by a general uplift ranging from a few hundred feet to a thousand feet. The modern stream-dissected, hilly surface, with maximum valley depths of a few hundred feet, has developed on the rejuvenated surface. Throughout much of the Interior Lowland, the Pleistocene ice-sheets interrupted the normal work of erosion and filled many valleys with glacial drift. Many streams have since cleared out such valleys or cut through the drift mantle in new places. The history of the Great Lakes is considered in the next chapter.

*Ozark-Ouachita Highlands.* The so-called Interior Highland region of Missouri, Arkansas, and Oklahoma has been a land area since Late Paleozoic time. A general upward movement, involving several cycles (or partial cycles) of erosion and base-levelling, occurred during Mesozoic and Tertiary times. The peneplaned region was uplifted 1000 to 3000 feet in Late Tertiary time since which the highly stream-dissected surface of the present time has developed to a condition of maturity. Because of the folded structure of the strata, east-west ridges and valleys have been produced in the Ouachita Mountains, but, in the nearly horizontal strata of the Ozark Plateau, a very irregular ridge and valley pattern has resulted.

*Canadian Shield.* This vast area, comprising about one-fourth of North America (Fig. 1), has been subjected to erosion since middle Paleozoic time. Most of this time it was probably not high above sea level. In the Late Tertiary the low-lying Canadian Shield seems to have been notably elevated and stream-dissected. Then the great Pleistocene glaciers covered it. Late in the Pleistocene the region subsided to a level lower than that of today, submerging the Hudson Bay and much of the Arctic Islands regions. There is very strong evidence from elevated beaches, etc., especially in the southeast, that, in the present

(Recent) epoch, there has been a very considerable, though unequal re-elevation.

**Western North America.** *Great Plains.* This vast area, stretching from western Texas far northward into western Canada (Fig. 1), now rises from an altitude of about 1000 feet along its eastern margin to 4000 to 6000 feet along its western margin at the base of the Rocky Mountains. During most of Tertiary time the region was more nearly level, and, especially in the United States and southern Canada, it was the scene of widespread deposition of continental sediments. These sediments were carried out of the mountains and deposited in the form of flood-plain and alluvial-fan materials by the numerous graded and overloaded streams. Sediments of each Cenozoic epoch are represented, but the deposition varied a great deal both in time and place, and locally there was some erosion. The net result of these processes was the development of a plain of aggradation, with a smooth, nearly featureless surface, by Late Tertiary time. Since then the Great Plains region has been differentially uplifted to its present height and with its eastward down-tilt. Wide areas (e.g. northwestern Texas) are still remarkably smooth and little affected by erosion, while other regions of soft sediments, high above sea level, have been more or less deeply dissected, often into so-called "Badlands" (e.g. in southwestern South Dakota).

Pleistocene glacial deposition has often caused modifications of the topography in the northern part of the Great Plains.

The Black Hills of South Dakota stand out so boldly above the Great Plains because the core of a locally formed Late Cretaceous domal anticline, laid bare by erosion, there consists of very resistant pre-Paleozoic igneous and metamorphic rocks.

*Rocky Mountains.* Only a few of the more important features of the rather complex Cenozoic history of the Rocky Mountain region will be mentioned. The extensive folding, faulting, and vulcanism, which marked Late Cretaceous and Early Eocene times (Rocky Mountain Revolution), left the region topographically high and generally varied. Conditions were thus favorable for rapid erosion of the highlands and deposition of resulting sediments in intermontane basins during Eocene and Oligocene times. As indicated by the nature of the sediments (already described), all sorts of continental materials were laid down, such as lake, flood-plain, alluvial-fan, and volcanic fragmental deposits. Particular mention may be made of the thick and extensive lake beds of Eocene age in southern Wyoming and northern Utah.

Marine deposition was entirely lacking. The distribution of the various formations (Eocene and Oligocene) shows that the principal basins of deposition varied in time and place.

By Miocene time the general relief of the Rocky Mountain region was low because the highlands had been worn down and the basins largely filled with sediment.

FIG. 327. Remnant of a gently rolling (old age) surface 12,000 feet above sea level in the Rocky Mountains. In Middle Tertiary time it covered a wide region thousands of feet below its present level, and the peaks in the background of the picture were then monadnocks. Flattop Mountain, Rocky Mountain National Park, Colorado. (After W. T. Lee, U. S. Geological Survey.)

Vigorous and often long-continued volcanic activity took place throughout much of Tertiary time in various parts of the Rocky Mountains. Particular mention may be made of the tremendous accumulations of volcanic rocks in southwestern Colorado, and the volcanic plateau and mountains of Yellowstone Park. Small bodies of intrusive rocks were also emplaced here and there.

In later Tertiary and Quaternary times the general region was greatly rejuvenated by broad uplifts or upwarps, accompanied by very little folding, but with some notable faulting as along the eastern base of the Colorado Front Range, and the western base of the Wasatch Mountains in northern Utah. This uplift reached its climax in the Quaternary, but it was not continuous or uniform as proved by remnants of two or more base-levelled surfaces at widely different altitudes. One of these surfaces, called the Flattop peneplain, is remarkably well preserved at an altitude of about 12,000 feet in Rocky Mountain National Park (Fig. 327).

The late Cenozoic rejuvenation of the Rocky Mountains resulted in removal of much Tertiary material, and the bringing into strong relief of the older, harder rocks, by the revived streams. Thus in many cases the principal ranges of today, such as the Big Horn, Wind River, Uinta, Medicine Bow, Laramie, Colorado Front, and Sangre de Cristo

Ranges, consist of anticlinal cores of hard pre-Paleozoic granites, schists, etc. In other cases, such as the San Juan Mountains of Colorado and most of the mountains of Yellowstone National Park, much of the high, rugged relief is a result of vigorous erosion of nearly horizontal Tertiary volcanic rocks.

Pleistocene glaciers in the higher mountains produced many local effects of erosion and deposition.

*Colorado Plateau.* Eocene continental sediments were laid down extensively over much of the Colorado Plateau region, especially its northern half. Then followed a long interval of erosion interrupted by some broad, gentle folds or upwarps in Miocene time. By Late Tertiary

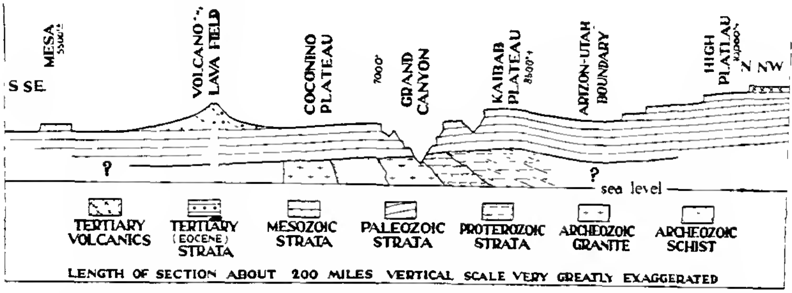



FIG. 328. A highly generalized structure section through the Colorado Plateau showing its principal topographic and geologic features. Note the general southward down-tilt; the Kaibab Plateau upwarp; the remnants of once more widespread Mesozoic and Cenozoic strata, with their steplike topography, at the upper right; the deep-cut Grand Canyon; and a Late Cenozoic volcano.

time the whole region was a low-lying peneplain. More or less extensive lava-flows spread over this peneplain and various volcanic peaks were built up, as for example in the large volcanic district in north-central Arizona. Tertiary laccolithic intrusions occurred in southeastern Utah.

Before the close of the Tertiary there was a moderate general uplift (hundreds of feet only), with some north-south faulting. This renewed the erosion which produced broad, shallow valleys and a steplike topography, the latter because escarpments were developed along outcrops of certain resistant formations.

The present cycle of erosion began in the Early Quaternary. It was introduced by a profound general uplift of the whole Colorado Plateau region, accompanied by a general northeasterly up-tilt (Fig. 328). In the south the plateau was brought to an altitude of about 5000 feet,

and in the north to more than 10,000 feet. The uplift caused a vigorous revival of stream erosion, particularly by the great Colorado River which has ever since been busily engaged in carving out the Grand Canyon of Arizona. There has also been some Quaternary volcanic activity as shown by the young cinder cones near Flagstaff, Arizona.

*Basin and Range Province.* This large physical province (Fig. 1) in the southwestern United States is characterized by many roughly parallel ranges separated by alluvial basins (bolsons). Altitudes vary from 276 feet below sea level in Death Valley, California, to over 13,000 feet in the Inyo-White Mountains of eastern California.

Most of the region was more or less strongly folded into mountains at the time of the Late Jurassic Sierra Nevada Revolution. During the Cretaceous period and most of the Tertiary, profound erosion reduced the whole region to low relief (old age).

In Late Tertiary time volcanic rocks (mainly lava-flows) covered many large and small parts of the old-age surface.

Beginning in the Late Tertiary, and continuing through the Quaternary, diastrophism (chiefly faulting) has been very active, resulting in the development of many fault-block mountains and intervening fault-trough valleys, an excellent example of the latter being Death Valley. In many places the once horizontal lava-flows may now be seen on the backs of block mountains (Fig. 330). The processes of faulting have varied a good deal in time and place throughout the province. For this reason many fault scarps are much more modified by erosion than others. Some high scarps are remarkably steep and comparatively little eroded (Fig. 331). In not a few cases fault scarps have recently formed across alluvial cones. Noticeable dislocations have occurred along some of the faults during the last fifty years.

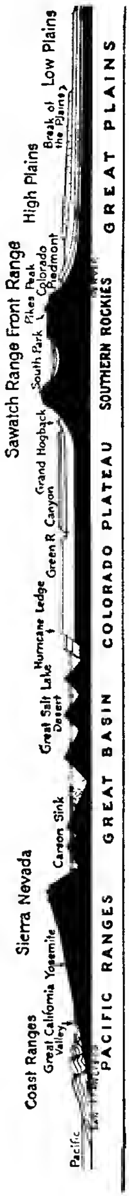



FIG. 329. A diagrammatic structure section across the western United States. The relations of various physiographic provinces are clearly shown. (Drawn by A. K. Lobeck.)

While the rising mountains have been eroded, the resulting debris has largely been carried into the intermontane basins, most of which

have no outlets to the sea. Thus the basins have been aggraded, often to depths of hundreds of feet. Viewed broadly most of the Basin and Range Province is in an early mature stage of the desert cycle of erosion.

Some volcanic action has continued through Quaternary time almost to the present day, as in Owen's Valley and the Mohave Desert, California, where remarkably fresh lava-flows have very recently spread

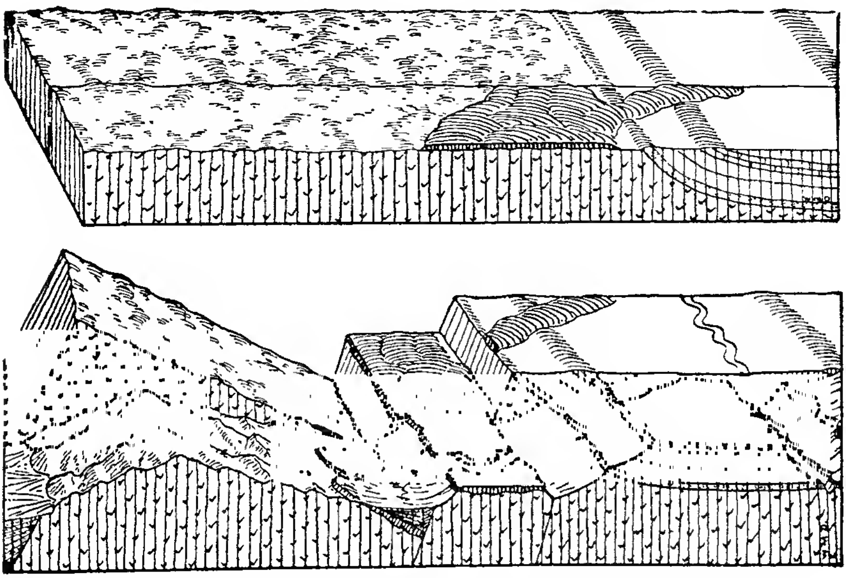


FIG. 330. Block diagrams illustrating typical stages in the later Cenozoic history of the Basin and Range Province. Upper diagram: back part shows the Late Tertiary peneplain, and front part the same partly covered with lava-flows. Lower diagram: back part shows the region after block faulting as it would appear if unaffected by erosion, and front part the actual present-day condition. The particular region here sketched includes the Peacock Range of western Arizona. (Drawn by W. M. Davis.)

over desert sands, and cinder cones are almost untouched by erosion (Fig. 332).

During Late Quaternary time the Basin and Range Province had a moister climate than at present, because lakes were much more numerous and larger than now. One of the largest of these was *Lake Bonneville,* Utah, which represented a greatly enlarged stage of the Great Salt Lake. Shoreline phenomena of this, and many of the other lakes, are often remarkably preserved.

*Columbia Plateau.* The building up of the vast lava region known as the Columbia Plateau, covering 200,000 square miles of the northwestern United States between the Cascade and Rocky Mountains, took place during Cenozoic time. It is one of the few greatest lava fields of the world. Fissure eruptions seem to have produced most of the lava-flows which commonly spread far from their sources, and piled up to thicknesses as great as 5000 feet or more. The vulcanism continued with more or less vigor through Tertiary time, but it was most pronounced and widespread in the Miocene epoch. It gradually diminished

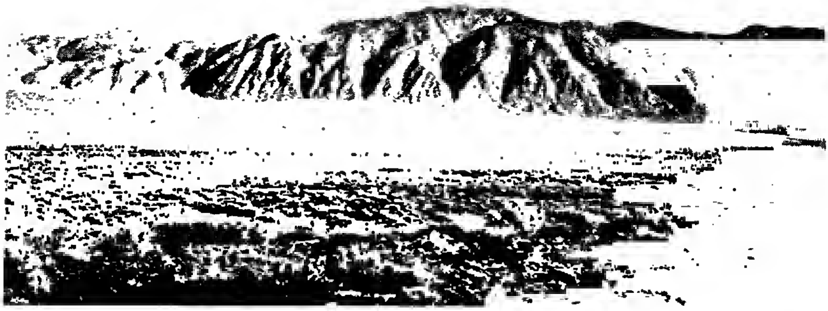


FIG. 331. Great fault-facets of Late Quaternary age on the side of Deep Spring Valley, California. The range rises 3000 feet above the valley floor. The slightly eroded triangular fault-facets are hundreds of feet high. (Photo by R. H. Mansfield.)

during the present (Quaternary) period, some of the most interesting, recent volcanic rocks being in Craters of the Moon National Monument in Idaho.

The evidence from some mountains not buried under the lava (e.g. Blue Mountains, Oregon) and from canyons where buried mountains have been exposed by erosion (e.g. Seven Devils Canyon of Snake River) shows that the pre-lava topography was that of late maturity or early old age of the normal cycle of erosion.

"For thousands of square miles the surface (of the plateau) is a lava plain which meets the boundary mountains as a lake or sea meets a rugged and deeply indented coast. . . . The rivers which drain the

plateau—the Snake, the Columbia, and their tributaries—have deeply trenched it, yet their canyons, which reach the depth of several thousand feet, have not been worn to the base of the lava except near the margin and where they cut the summits of mountains drowned beneath the flood. Here and there the plateau has been deformed. . . . The plateau has been built like that of Iceland, of innumerable overlapping sheets of

FIG. 332. A recent cinder cone on the Mohave Desert near Amboy, California.

lava. . . . The average thickness of flows seems to be about seventy-five feet.

"The plateau was long in building. Between the layers are found in places old soil beds and forest grounds and the sediments of lakes. . . . So ancient are the latest floods in the Columbia Basin that they have weathered to a residual yellow clay from thirty to sixty feet in depth and marvelously rich in the mineral substances on which plants feed. In the Snake River Valley the latest lavas are much younger. Their surfaces are so fresh and undecayed that here the effusive eruptions may have continued to within the period of human history." [1]

It should not be understood that all the rocks are lavas. In various places and at different times, fragmental materials accumulated, often to depths of hundreds of feet. A good case in point is the John Day

[1] W. H. Norton: *Elements of Geology*, pp. 400–401.

formation of Oregon (Fig. 334). During and after the main eruptions there was some gentle folding, faulting, and general warping of the region. Mention may be made of a large body of water, called *Lake Payette,* which came into existence because of such deformation in the

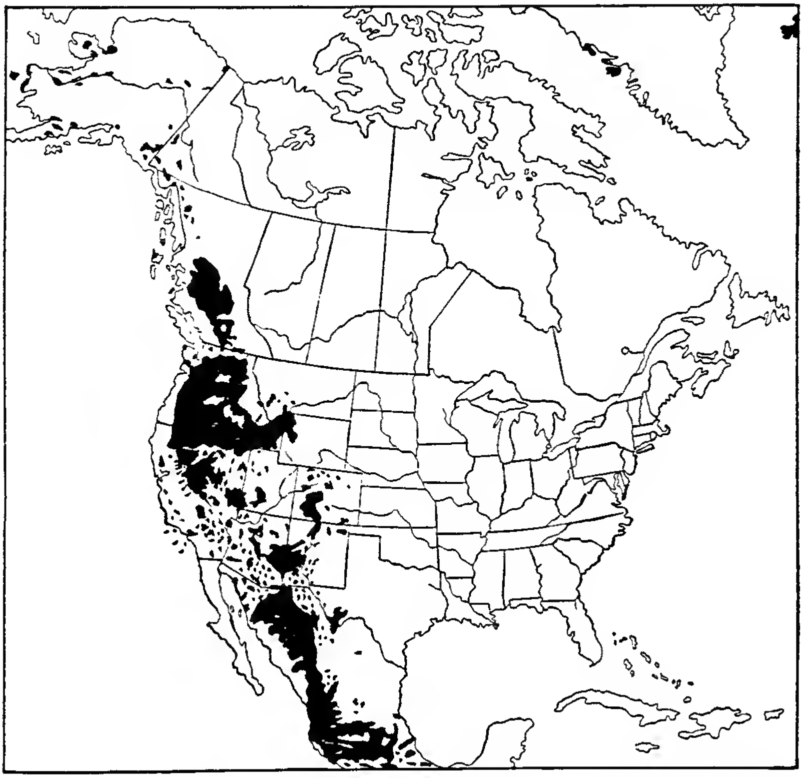


FIG. 333. Map showing the surface distribution (areas of outcrops) of Cenozoic volcanic rocks in North America. (Principal data from the U. S. Geological Survey.)

midst of Tertiary time in eastern Oregon-western Idaho. The extensive lake beds are rich in fossil plants.

*Cascade Mountains.* The Cascade Mountain region, extending from the Lassen Peak district in northern California through Oregon and Washington (Fig. 1), was more or less folded and elevated into mountains toward the close of Jurassic time. During Cretaceous and earlier Tertiary times there was profound erosion of the region. Great volcanic activity, mainly in the form of lava outpourings, occurred in the later

Tertiary. These volcanics piled up to such a great extent as almost completely to bury the pre-Tertiary rocks in the middle and southern parts of the Cascade region. By latest Tertiary or Early Quaternary time most of the region, particularly in northern Washington, was in an old age or peneplain stage of erosion.

Early in the Quaternary there was a great rejuvenation of the Cascade region by uplift, accompanied by warping and gentle folding, to form a plateau 4000 to 8000 feet above sea level. That portion of

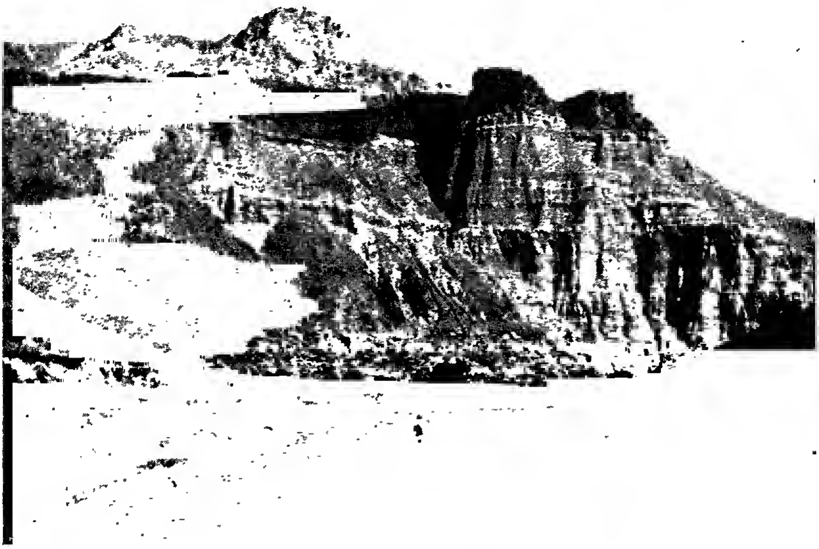


FIG. 334. An exposure of the John Day formation of Oligocene-Miocene age 15 miles north of Dayville, Oregon. The nearly horizontal beds of buff and green tuffs contain an interbedded sheet of red rhyolitic lava (darker layer) in its upper part. (Photo by R. W. Chaney.)

the range which is cut through by the Columbia River was bowed up several thousand feet in the form of a broad anticline or upwarp, 40 miles wide, with its axis parallel to that of the mountains, and the river maintained its course, as an antecedent river, during the uplift.

During and since the rejuvenation, the plateau has been deeply dissected by streams aided somewhat by glaciers. In the meantime numerous large volcanoes were active from one end of the range to the other, building up a string of cones above the general level of the plateau surface. Among these cones are Lassen Peak, Mt. Shasta, Mt.

Pitt, Mt. Hood. Mt. Rainier, and Mt. Baker. Many of the larger cones supported glaciers during the Pleistocene period, and some of them, particularly Mt. Rainier, still do.

Crater Lake, Oregon, 2000 feet deep and nearly 6200 feet above sea level, partly fills a crater pit (or caldera) about 6 miles in diameter (Fig. 335). The caldera resulted from the collapse and engulfment (or possibly explosion) of the upper portion of a once great volcanic cone known as Mt. Mazama. Glacial deposits have recently been found interbedded with volcanic rocks in the walls of the caldera facing Crater Lake, thus proving that glaciers existed on Mt. Mazama from time to time while it was building up.

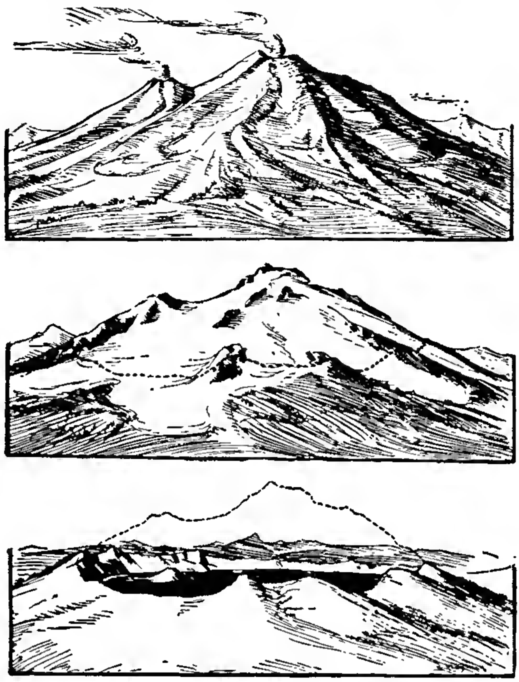


FIG. 335. Sketches illustrating the later history of Mt. Mazama, Oregon. Upper: the full-grown active volcano in Late Pleistocene time. Middle: the cone draped with glaciers during the Late Pleistocene. Lower: the mountain as it now appears after destruction of the cone and partial filling of the resulting great crater pit with water to form Crater Lake. (After W. W. Atwood, Jr.)

A cinder cone and small lava field near Lassen Peak, California, are very young, the latest lava having poured out during the middle of the 19th century. Lassen Peak itself was explosively active during the years 1914-1916.

*Sierra Nevada Range.* This mountain range extends 500 miles through eastern California and rises to a maximum altitude of 14,496 feet in Mt. Whitney.

As we have already learned, the Sierra Nevada region was highly folded, intruded with granite batholiths, and elevated into lofty mountains toward the close of the Jurassic period. During the Cretaceous

the mountains were worn down to a lowland condition. In the Eocene epoch there was sufficient rejuvenation to cause revived streams to cut canyons 1000 to 2000 feet deep. Many of the famous gold-bearing gravels of the region then accumulated in the stream beds. Volcanic rocks, particularly tuffs, then buried most of the gold-bearing gravels.

During most of Oligocene and Miocene times, profound erosion reduced the whole Sierra Nevada region to a topographic condition of early old age. Late in the Miocene large parts of the old surface, mainly in the north, were covered with lava flows.

At the end of the Miocene another rejuvenation occurred, this time in the form of a tilted fault-block with a scarp about 3000 feet high along the eastern side, and a much more gradual slope down the western side.

The Pliocene epoch was a time of erosion when the main streams cut canyons 1000 to 1500 feet deep into the western slope.

Early in the Quaternary there began a great renewed uplift of the tilted Sierra Nevada fault-block which continued through the period, giving rise to the present-day, lofty range. The streams, which became not only swifter but also larger, deepened the Pliocene canyons so that now many of them are 3000 to 6000 feet deep (e.g. King's River Canyon). Valley glaciers (often very large ones) occupied parts of many of the canyons, and helped to deepen them somewhat and change their shapes, during the Pleistocene Ice Age, as in the case of Yosemite Valley (Fig. 342).

*Coast Range of the United States.* During the Eocene epoch much of western California, Oregon, and Washington were under the sea most of the time (Fig. 321). Eocene lavas poured out in western Washington and Oregon.

The Oligocene was marked by somewhat greater elevation of the coastal region, causing the sea to be much more restricted (Fig. 322). Non-marine beds, such as the Sespe formation in southern California, piled up in various places.

Submergence of the coastal region, comparable to that of the Eocene, marked earlier Miocene time. In the midst of the Miocene there was pronounced diastrophism, involving local folding and uplift, in the Coast Range region. There were great extrusions of volcanic rocks at this time in southern California. The later Miocene was another important time of subsidence, particularly in California where the western one-third of the state was submerged. Sediments piled up to great thicknesses in the Miocene seas.

In the Pliocene and earliest Pleistocene the seas were much more restricted than in the Miocene, but in southern California conditions for rapid sedimentation in local basins were so favorable (e.g. Ventura region) that marine strata piled up to the phenomenal thickness of 20,000 feet in such a short time. Non-marine beds of Pliocene and Early Pleistocene ages also accumulated in many places. Considerable

FIG. 336. Locally folded marine strata of Tertiary age in the Coast Range Mountains. Near Las Cruces, California.

Pliocene vulcanism occurred in the northern Coast Range region of California.

Well after the opening of the Pleistocene epoch, there was general elevation and great deformation, including much folding and faulting, throughout the Coast Range region. This orogeny, called the *Coast Range Revolution*, has not ended as evidenced by fault movements such as that along part of the great San Andreas fault in 1906. Strata, often 20,000 to 40,000 feet thick, have been more or less profoundly affected by the disturbance. In various places strata as young as Early Pleistocene show strong effects of the diastrophism. The revolution has involved a series of movements varying in intensity, time, and place.

The Great Valley of California, little affected by folding and faulting during Quaternary time, lay between the rising folds of the Coast

Range Mountains on the west and the rising Sierra Nevada fault-block on the east.

There are many records of later Quaternary ups and downs in the Coast Range region of the western United States, often amounting to hundreds of feet, as shown by uplifted marine terraces, and by sunken areas such as San Francisco Bay and Puget Sound.

*Southwestern California.* Some of the principal mountains of southwestern California are the San Gabriel, San Bernardino, San Jacinto,

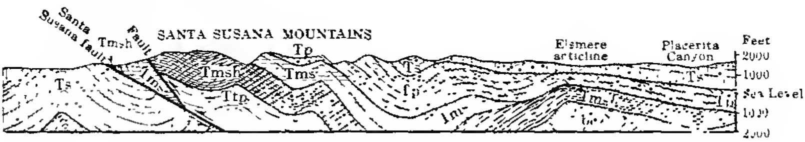



FIG. 337. A nearly north-south structure section through a part of western Los Angeles County, California, proving that the region was strongly folded and faulted after Early Pleistocene (Saugus) strata were deposited. Length of section, 6.5 miles. Symbols: *bc* = pre-Cretaceous crystalline rocks; *Ttp* = Miocene (Topanga) sandstone; *Tmsh*, *Tms* = Miocene (Modelo) shale and sandstone; *Tp* = Late Pliocene (Pico) sandstone; and *Ts* = Early Pleistocene (Saugus) sandstone. (After W. S. Kew, U. S. Geological Survey, Bul. 753.)

and Peninsular Ranges (Fig. 1). They have many points reaching altitudes of 6000 to over 11,000 feet.

During Eocene, Miocene, and Pliocene times the sea spread over the coastal part of southwestern California, including the sites of some of the smaller ranges. Sediments piled up to a great thickness in these marginal seas, particularly in the Los Angeles Basin where Tertiary strata are fully 20,000 feet thick. In Pliocene time the Gulf of California extended farther north than it does today (Fig. 324).

The Tertiary upland region (usually mountainous) facing the marginal seas consisted mostly of hard igneous and metamorphic rocks of pre-Cretaceous age. It was inherited from the mountains formed during the Sierra Nevada Revolution. By Early Pleistocene time the upland region was reduced to an old age or peneplain condition.

Profound diastrophic activity during Quaternary time has resulted in the uplift of large and small bodies of the old hard rocks of the worn-down upland region, in the form of fault blocks, to various heights (Fig. 338). In most cases the mountain blocks rose thousands of feet as so-called horsts between two faults (e.g. San Gabriel Mountains, Fig. 338), while in other cases they were upraised as tilted blocks

(e.g. Santa Ana Mountains). These mountains have been deeply stream-dissected to a stage of late youth or early maturity. In many places distinct remnants of the former old-age surface are now preserved thousands of feet above sea level. There is some evidence of former small glaciers in the higher mountains.

The Quaternary diastrophism excluded the marginal sea from the coastal belt, and more or less folded the Cenozoic strata. Much alluvial material, carried out of the mountains by streams, has accumulated over the coastal belt as a surface deposit, often hundreds of feet thick.

FIG. 338. Part of the San Gabriel Mountains rising 5000 feet above Pasadena, California. These mountains were upraised mainly in earlier Quaternary time. The steep front of the range is a fault scarp much modified by erosion. There are deep canyons back in the mountains. (Photo by J. E. Wolff.)

The islands off the coast of southern California were also separated from the mainland by the Quaternary diastrophism.

Uplifted marine terraces are indicators of recent movements along the coast.

*Klamath Mountains.* The Klamath Mountains of southwestern Oregon and northwestern California (Fig. 1) had a pre-Cenozoic history much like that of the Sierra Nevada. Their former connection with the latter was buried under great accumulations of Tertiary volcanics.

The mountains formed in Late Jurassic time were reduced to a peneplain by Late Miocene time; uplifted with warping in the Early Pliocene; reduced to low relief again by Late Pliocene time; and generally rejuvenated by several thousand feet of uplift in the Early Quaternary, thus starting the present cycle of erosion during which the old (plateau) surface has been highly dissected. There were some small Pleistocene glaciers.

*Alaska and Western Canada.* The later geologic history of this large and complicated Cordilleran region is much less well known than that of the western United States. It involved much mountain-making, including folding of strata and batholithic intrusion, in later Mesozoic time, particularly in the Coastal Range and in the Endicott Mountains each of which extends partly through the region; much reduction of the region by erosion during the Tertiary; marine invasions of small parts of the coastal regions in the Tertiary; vulcanism in the Tertiary; widespread Quaternary elevation to about the present altitude; deep dissection of the elevated region by erosion; and continued vulcanism to the present day, especially in the Alaska Peninsula-Aleutian Islands region. Various local changes of level have occurred in later Quaternary time. The numerous glaciers of Alaska, and some in southern British Columbia, are but remnants of the more extensive Pleistocene glaciers.

*Western Mexico.* The later geologic history of western Mexico, including Lower California, involved mountain-making with folding of strata and batholithic intrusions, in later Mesozoic time; the cutting down of the mountains during the Tertiary; tremendous and widespread volcanic activity during the Tertiary (Fig. 333); an enlarged Gulf of California in the Pliocene (Fig. 324); general Quaternary elevation and erosion; and vulcanism, bringing about present-day conditions.

## Cenozoic Climate

During Early Eocene time the climate of North America was in general notably cooler and drier than that of the present day. This was due mainly to the influence of the great newly formed Rocky Mountains. Glacial deposits of Early Eocene age have been found in Colorado.

From Middle Eocene to Middle Miocene time North America had in general a warm-temperate, moist climate because the high mountains of the west were in such a worn down condition that the warm

moisture-laden winds from the Pacific were free to sweep across the relatively low lands.

Viewed in a broad way, the climate of the continent gradually became cooler and drier from the Middle Miocene to the Late Pliocene, inclusive, in places reaching Arctic conditions. This was caused by widespread uplifts of the land over the continent, but more especially in the Cordilleran region.

The grand climax of Cenozoic cold was reached in the succeeding Glacial epoch of the Quaternary period.

# CHAPTER XXIV

## QUATERNARY ICE AGE

### The Fact of the Ice Age

The Quaternary period was ushered in by the spreading of vast ice sheets over much of northern North America and northern Europe. This event must take rank as one of the most interesting and remarkable occurrences in geological time. On first thought, the existence of such vast ice sheets seems unbelievable, but the Ice Age occurred so short a time ago that the records of the event are perfectly clear and conclusive. The fact of this great Ice Age was discovered by Louis Agassiz in 1837, and fully announced before the British Scientific Association in 1840. For some years the idea was opposed, especially by advocates of the so-called iceberg theory. Now, however, no important event of earth history is more firmly established and no student of the subject ever questions the fact of the Quaternary Ice Age.

### Ice Extent and Centers of Accumulation

The accompanying map (Fig. 339) shows the area of nearly 4,000,000 square miles of North America covered by ice at the time of maximum glaciation, and also the three great centers of accumulation and dispersal of the ice. The directions of flow of the ice from these centers have been determined by the study of the directions of a very large number of glacial striæ, as well as the direction of transportation of the glacial débris. Greenland was also buried under ice during the Quaternary period.

Two striking features regarding the distribution of the ice were (1) the failure of the ice to cover any of Alaska except its high mountain regions, though that country is much farther north than most of the glaciated area; and (2) the failure of anything like continuous ice sheets over the high plateaus of the western United States, while the great ice sheet spread over much of the low plains area of the upper Mississippi Basin.

From its center of accumulation, the Labradorean ice sheet extended fully 1600 miles southwestward or to about the mouth of the Ohio River. The Keewatin sheet extended from its center southward nearly as far, or into northern Missouri. These two great ice sheets prac-

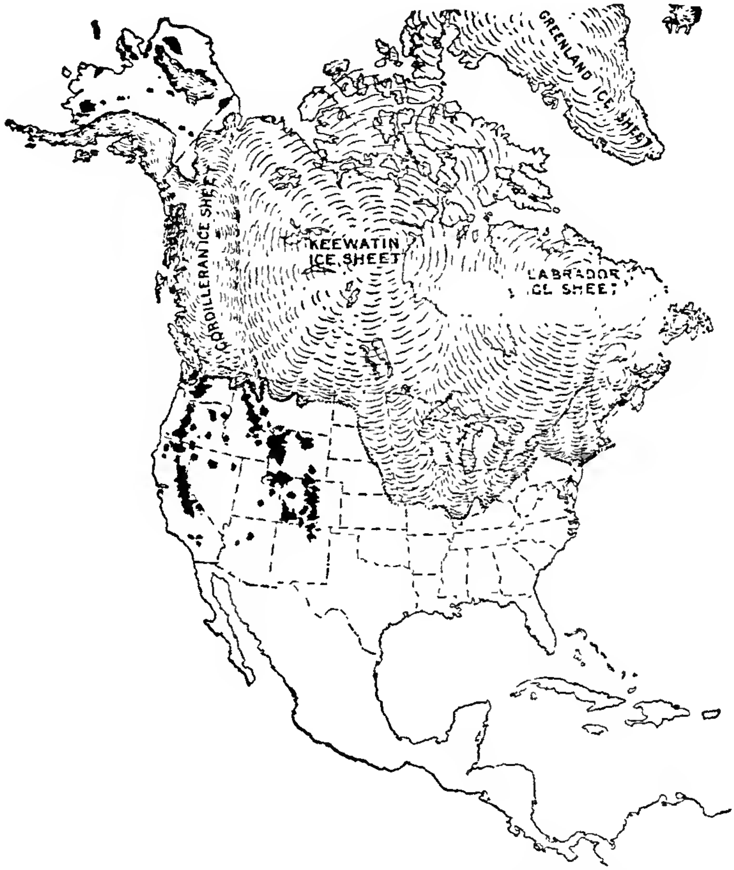



FIG. 339. Map of North America showing the maximum extent of glaciers during the Pleistocene Ice Age. The locations and general directions of movement of the great ice sheets are indicated, and regions of local mountain glaciers are shown in black. (Modified after U. S. Geological Survey.)

tically merged. "One of the most marvelous features of the ice dispersion was the great extension of the Keewatin sheet from a low flat center westward and southwestward over what is now a semiarid plain, rising in the direction in which the ice moved, while the mountain glaciers on

the west, where now known, pushed eastward but little beyond the foothills" (Chamberlin and Salisbury).

The Cordilleran ice sheet appears to have been mostly made up of both plateau and typical mountain (Alpine) glaciers. Toward the south it extended only a little way over the high mountains of the northwestern United States.

Newfoundland probably had a local center of glaciation.

South of the ice sheets above described, the higher mountains of the United States, even as far south as southern California, Arizona, and New Mexico, bore numerous glaciers greatly varying in size (Fig. 339). These were always of the typical valley or Alpine types instead of ice sheets. Some of these mountains, such as Shasta, Hood, Rainier, and those of the Glacier National Park in Montana, still have glaciers, the greatest being those on Mount Rainier, where they attain lengths of from 4 to 6 miles. The Pleistocene glaciers were, however, far larger and more numerous in these mountain regions (Fig. 339).

## Direction of Movement and Depth of Ice

The fact that glacial ice flows as though it were a viscous substance is well known from studies of present-day glaciers in the Alps, Alaska, and Greenland. A common assumption, either that the land at the center of accumulation must have been thousands of feet higher, or that the ice must have been immensely thick, in order to permit flowage so far out from the center, is not necessary. For instance, if one proceeds to pour viscous tar slowly in one place upon a perfectly smooth (level) surface, the substance will gradually flow out in all directions, and at no time will the tar at the center of accumulation be very much thicker than at other places. The movement of the ice from each of the great centers was much like this, only in the case of the glacier the piling up of snow and ice was by no means confined to the centers of accumulation.

Evidences of glaciation, such as striæ, boulders, lakes, etc., occur high up in the Adirondacks, the Catskills, the Green and the White Mountains, and the Berkshire Hills, so that the greatest depth of ice over New York and New England could not have been less than one or two miles. In fact we have every reason to believe that all of the mountains named were completely buried. The reader may wonder how the ice over a mile thick in northern New York could have thinned out to disappearance at or near the southern border of the state, but observations on existing glaciers show that it is quite the habit of extensive ice

bodies to thin out very rapidly near the margins, thus producing steep slopes along the ice fronts.

There is little reason to doubt that the vast ice sheet over the upper

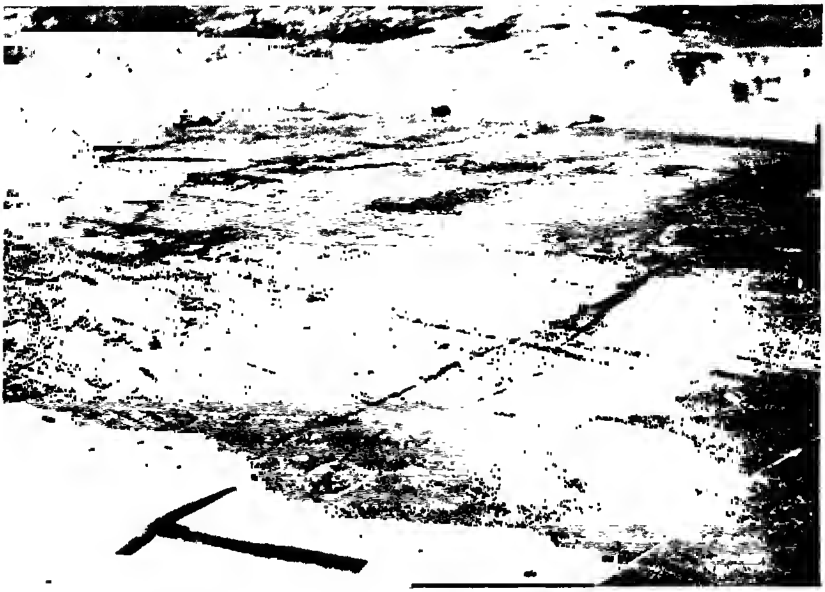


FIG. 340. A remarkable record of two glaciations hundreds of millions of years apart. Thoroughly consolidated boulder-bearing glacial till of Proterozoic (Huronian) age which has been planed off, striated, and polished by a Pleistocene ice sheet. Near Thessalon, Ontario, Canada. (Photo by A. P. Coleman.)

Mississippi Valley was also thousands of feet thick. The positions of the moraines there clearly prove that the ice front was more or less distinctly lobate.

## Successive Ice Invasions

The front of the great ice sheet, like that of ordinary valley glaciers, must have shown many advances and retreats. In the northern Mississippi Valley, however, we have positive proof of several important advances and retreats of the ice which gave rise to true interglacial stages. The strongest evidence is the presence of successive layers of glacial debris, a given layer often having been oxidized, eroded, and covered with vegetation before the next (overlying) layer was deposited (see Fig. 341). In drilling wells through the glacial deposits of Iowa, for example, two distinct layers of vegetation are often encountered at

depths of from 100 to 200 feet. Near Toronto, Canada, plants which actually belong much farther south in a warm climate have been found between two layers of glacial debris. Thus we know that some, at least, of the ice retreats produced interglacial stages with warmer climate and were sufficient greatly to reduce the size of the continental ice sheet or possibly to cause its entire disappearance.

By applying the principles just laid down, at least four advances and retreats of the ice, with distinct interglacial intervals, have been recognized in North America as follows:

| Period (System) | Epoch (Series) | Age (Stage) | | "Epochs" after Kay & Leighton |
|---|---|---|---|---|
| Quaternary | Recent | Post-Glacial | | |
| | Pleistocene | Wisconsin (glacial) (Peorian loess) | Mankato<br>Cary<br>Tazewell<br>Iowan | Eldoran |
| | | Sangamon (interglacial)<br>Illinoian (glacial) | | Centralian |
| | | Yarmouth (interglacial)<br>Kansan (glacial) | | Ottumwan |
| | | Aftonian (interglacial)<br>Nebraskan (glacial) | | Grandian |

The various glacial and interglacial deposits are by no means everywhere always present, first, because, in many places, older deposits were eroded away before younger deposits were laid down, and, second, be-

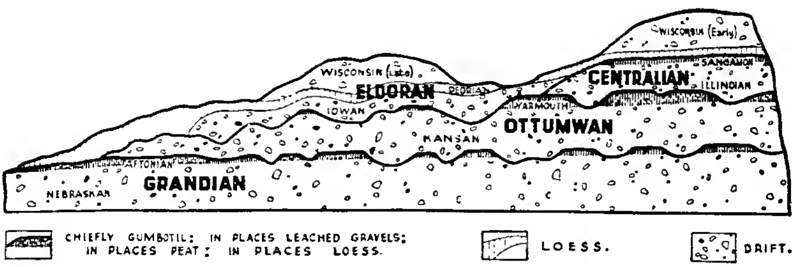



FIG. 341. Diagrammatic structure section showing relationships of the main divisions and subdivisions of the Pleistocene deposits in the Mississippi Valley. (After G. F. Kay.)

cause the various ice sheets differed considerably in regard to the areas they covered, especially within a few hundred miles of the southern limit of glaciation. Thus in Figure 341 the Centralian deposits are

seen to be missing between the Eldoran and Ottumwan over a large region.

In New York and New England no very positive evidence has as yet been found to prove truly multiple glaciation, though some phenomena as, for example, certain buried gorges, are difficult to account for except on the basis of more than one advance and retreat of the ice. At any rate, there appears to be no good reason to believe that there were more than two advances and retreats of the ice over this region.

For our purpose in considering only the general movements and effects of the great ice sheets, we may practically disregard the problem of multiple glaciation, because the final effects would have been essentially the same as a result of a single great glacial advance and retreat.

Recent studies have shown that multiple glaciation also occurred in the mountains of the west (Cordilleran region), beyond the limits of the vast ice sheets, during the Ice Age. Thus, in the Sierra Nevada Mountains of California, valley glaciers came and went three (and possibly four) times, as indicated by several glacial deposits of distinctly different ages. These glacial stages very likely correlate with stages of the great ice sheets.

## The Driftless Areas

In southwestern Wisconsin, and extending a little into adjoining states, there is a non-glaciated area of about 10,000 square miles which lies several hundred miles north of the southern limit of the ice sheets (see Fig. 339). This is called a "driftless area," because of the utter absence of glacial debris or any other evidence of glaciation within its boundary. In spite of several ice invasions on all sides, this small area was never ice covered. Residual soils and rotten rock are widespread; there are no lakes; and the streams are mostly graded and without waterfalls or rapids. This small region, therefore, gives an excellent idea of the kind of topography which the whole upper Mississippi Valley would have shown had it not been for the glaciation. At no time did the Labradorean ice sheet spread far enough westward, or the Keewatin sheet far enough eastward, to cover this driftless area. The highland district just south of Lake Superior doubtless served to deflect and weaken the flow of the Labradorean ice which otherwise might have spread far enough to have covered the driftless area.

A much smaller driftless area has more recently been discovered along the Mississippi River in Missouri. It is not difficult to under-

stand why such an area so close to the southern limit of glaciation escaped all advances of the ice sheets.

The probable explanation of the extensive driftless areas in Alaska is that, in spite of the low temperatures which must have prevailed, there was insufficient snow for conversion into glacial ice.

## Ice Erosion

In former years a very great erosive power was ascribed to flowing ice, but today some glacialists consider ice erosion to be almost negligible, while many others maintain that, under favorable conditions, flowing ice may produce very notable erosive effects. During the long pre-Glacial time, rock decomposition must have progressed so far that rotten rock, including soils, had accumulated to considerable depths, as today in the southern states. Such soils are called "residual," because they are derived by the decomposition of the very rocks on which they rest. But now one rarely sees rotten rock or soil in its original position well within the glaciated area, because such materials were nearly all scoured off by the passage of the great ice sheet, mixed with other soils and ground up rock fragments, and deposited elsewhere. Such are called transported soils. Along the southern side of the glaciated area, where the erosive power of the ice was least, rotten rock is more common. Ice, shod with hard rock fragments and flowing through a deep, comparatively narrow valley of soft rock, is especially powerful as an erosive agent, because the tools are supplied, the work to be done is easy, and the increased depth of the ice where crowded into a deep, narrow valley causes greater pressure on the bottom and sides of the channel. Many of the valleys of northern New York were thus favorably situated for ice erosion, as, for example, the Champlain, St. Lawrence, Black River, Finger Lakes valleys. Even in places so favorably situated as those just mentioned there is no reason to believe that ice erosion did any more than to modify the profiles of the pre-Glacial valleys.

It is also a singular fact that glacial deposits left by one ice sheet may actually have been overridden by a later advance of ice with little erosion of even such soft material. This probably happened only near the margin, where the ice was rather thin and hence did not have much erosive power.

In conclusion we may say that while many comparatively small, local features were produced by ice-sheet erosion, the major topographic

features of the great glaciated areas were practically unaffected by the abrasive effects of the passing ice sheets.

Local mountain glaciers often produced notable effects in canyons beyond the limits of the great ice sheets, changing their profiles from

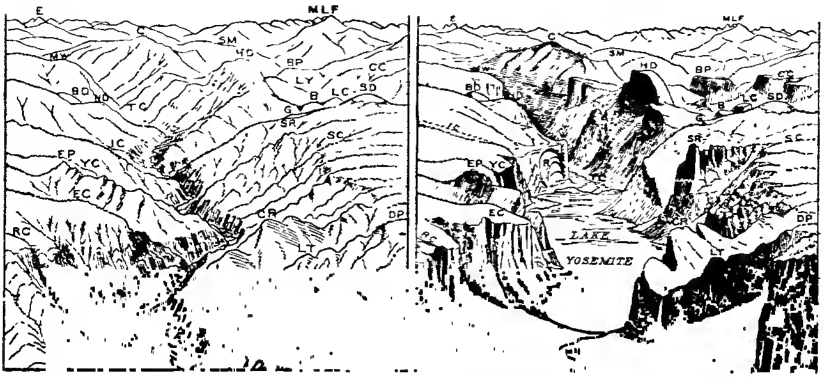



FIG. 342. Sketches showing how the Yosemite Valley, California, region appeared just before and after glaciation. A deep stream-cut canyon, with a conspicuous inner gorge, was changed into a profound U-shaped trough by glacial erosion. Lake Yosemite has since been filled with sediment. *EC*, El Capitan; *YC*, Yosemite Creek; *ND*, North Dome; *HD*, Half Dome; *G*, Glacier Point; *CR*, Cathedral Rocks; *BV*, Bridalveil Creek; and *MR*, Merced River. (After F. E. Matthes, U. S. Geological Survey.)

V-shape to U-shape. There are many excellent examples in Glacier National Park, Rocky Mountain National Park, and in the Cascade-Sierra Nevada Mountains. An exceptionally fine case in point is Yosemite Valley, California (Fig. 342).

## Ice Deposits

The vast amount of débris transported by a great ice sheet was carried either on its surface, frozen within it, or pushed along beneath it. It was heterogeneous material ranging from the finest clay, through sand and gravel, to boulders of many tons' weight. The deposition of these materials took place during both the advance and retreat of the ice, but chiefly during its retreat. Most of the deposits made during the last ice advance were obliterated by ice erosion, while those formed at the time of the retreat have been left intact except for the small amount of post-Glacial erosion and weathering. The term "drift," applied to all deposits of glacial origin, was given at a time when they

were regarded as flood or iceberg deposits. Drift covers practically all of the glaciated region except where bare rock is actually exposed, and its thickness is very variable, ranging from nothing to some hundreds of feet.

The various kinds of glacial deposits and their origin are discussed in Chapter VIII, Part I, of "Elements of Geology."

## The Loess Deposits

Loess deposits are widespread over much of the region from eastern Nebraska, across Iowa, Illinois, and Indiana. Its distribution is rather largely independent of topography. Typically it is a soft, buff to yellowish-brown, very fine grained, sandy clay which seldom shows signs of stratification. Its thickness usually varies from 10 to 100 feet. Where eroded or cut into, the loess exhibits a remarkable tendency to stand in perpendicular cliffs, sometimes with suggestions of a sort of columnar structure. For this reason it was once known as the Bluff formation. Most of it is now known as the Peorian loess. It is remarkably free from coarse materials, except for certain carbonate of lime and oxide of iron concretions and fossils, the latter being chiefly shells of land gastropods. Most of the loess was deposited during an early Wisconsin sub-stage, because it rests upon the eroded and weathered surfaces of older glacial deposits, including those of the Iowan sub-stage, and often passes under later Wisconsin deposits (Fig. 341).

The question as to whether the loess was of aqueous or eolian origin has long been discussed. "In part the loess seems to have been washed from glacial waste and spread in sluggish glacial waters, and in part to have been distributed by the wind from plains of aggrading glacial streams" (W. H. Norton).

## Great Lakes History

The Great Lakes certainly did not exist before the Ice Age. During the very long erosion period from the Paleozoic to the Cenozoic, no lakes of any consequence could have persisted. Compared with such an immense length of time lakes are, at most, only ephemeral features of the earth's surface because they are soon destroyed either by being filled with sediments, or by having their outlets cut down, or both. Since the Great Lakes are of post-Glacial origin it is, then, proper to ask how they came into existence. During pre-Glacial time broad valleys were cut out along belts of weak rock in the Great Lakes region, and these old

valleys, to a considerable extent at least, account for the present depressions, but not for the closed lake basins. This idea of pre-Glacial stream valleys is not at all opposed by the fact that some of the lake bottoms are now well below sea level, because there has been notable subsidence of the region since pre-Glacial time. Strong arguments might be adduced to show that by ice erosion portions, at least, of all the lake basins were appreciably deepened. Even so, however, we have not yet accounted for the present closed basins. Deep drift deposits must certainly have been very effective in damming up the south or southwest-flowing pre-

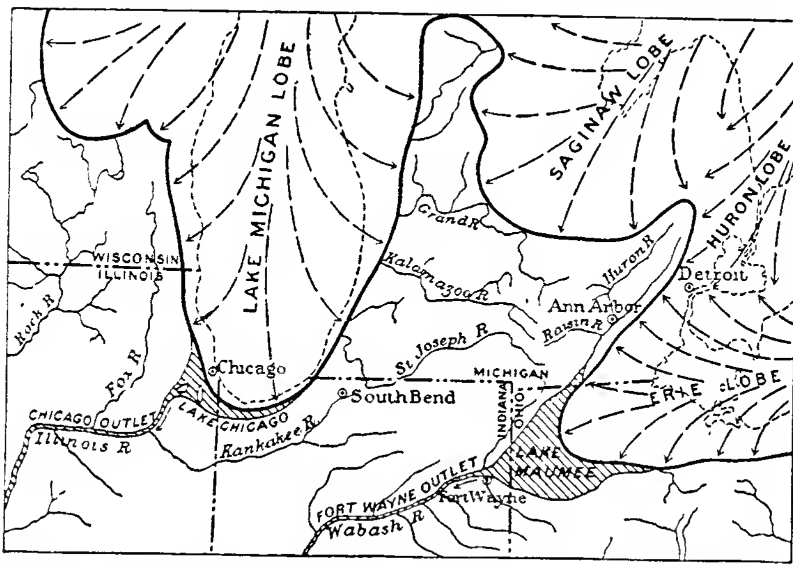



FIG. 343. First stage in the history of the Great Lakes. Note the small ice-front lakes (Maumee and Chicago). (After U. S. Geological Survey.)

Glacial streams of the region because a great dumping ground of ice-transported materials from the north was in general along the southern side of the Lakes and southward. Late in the Ice Age the land on the northern side of the Great Lakes region was lower than it is today, as proved by the tilted character of certain well-known beaches of extinct lakes (see below). Such a differential tilting or warping of the land must have helped to form the closed basins by tending to stop the southward or southwestward drainage from the region.

We shall now trace out the principal stages in the history of the Great Lakes region during the final retreat of the great ice sheet. When the ice front had receded far enough northward to uncover the

southern end of Lake Michigan, and an area west of the present end of Lake Erie, small lakes were formed against the ice walls (see Fig. 343). The first of these has been called Lake Chicago, which drained past Chicago through the Illinois River and into the Mississippi; and the second, Lake Maumee, which drained southwestward past Fort Wayne through the Wabash River and thence into the Ohio and Mississippi.

At a later stage the conditions shown on map, Figure 344 existed. Lake Chicago was then larger, and Lake Maumee had expanded into the extensive Lake Whittlesey, which covered nearly all of the area of Lake Erie as well as some of the surrounding country. Lake Whittlesey was at a lower level than the former Maumee, and the outlet past Fort

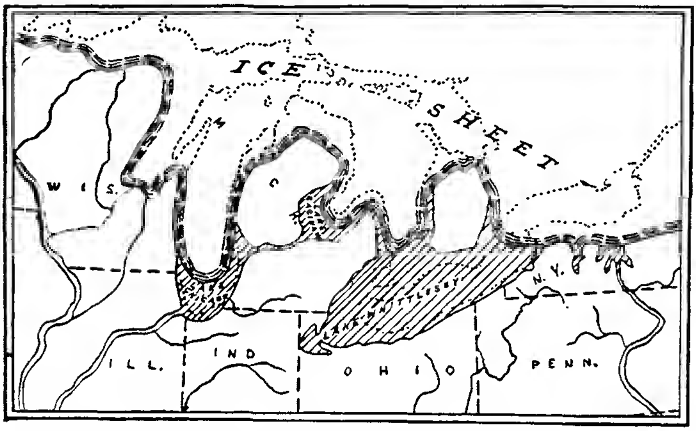



FIG. 344. Lake Whittlesey stage of the Great Lakes history, when the eastern and western ice-margin lakes combined with outlet past Chicago. (After Taylor and Leverett, redrawn by W. J. M.)

Wayne ceased, but the drainage from Whittlesey was westward by a large river flowing through small Lake Saginaw and into Lake Chicago, which later still emptied through the Illinois River.

At a considerably later stage three large, ice-border lakes—Duluth, Chicago, and Lundy—existed as shown by map, Figure 345. Each had a separate outlet, the first two draining into the Mississippi, and the last through the Mohawk and Hudson valleys of New York into the Atlantic Ocean.

With a still greater retreat of the ice sheet came the Algonquin-Iroquois stage as shown by map, Figure 346. Lake Iroquois covered somewhat more than the present area of Lake Ontario, and the dis-

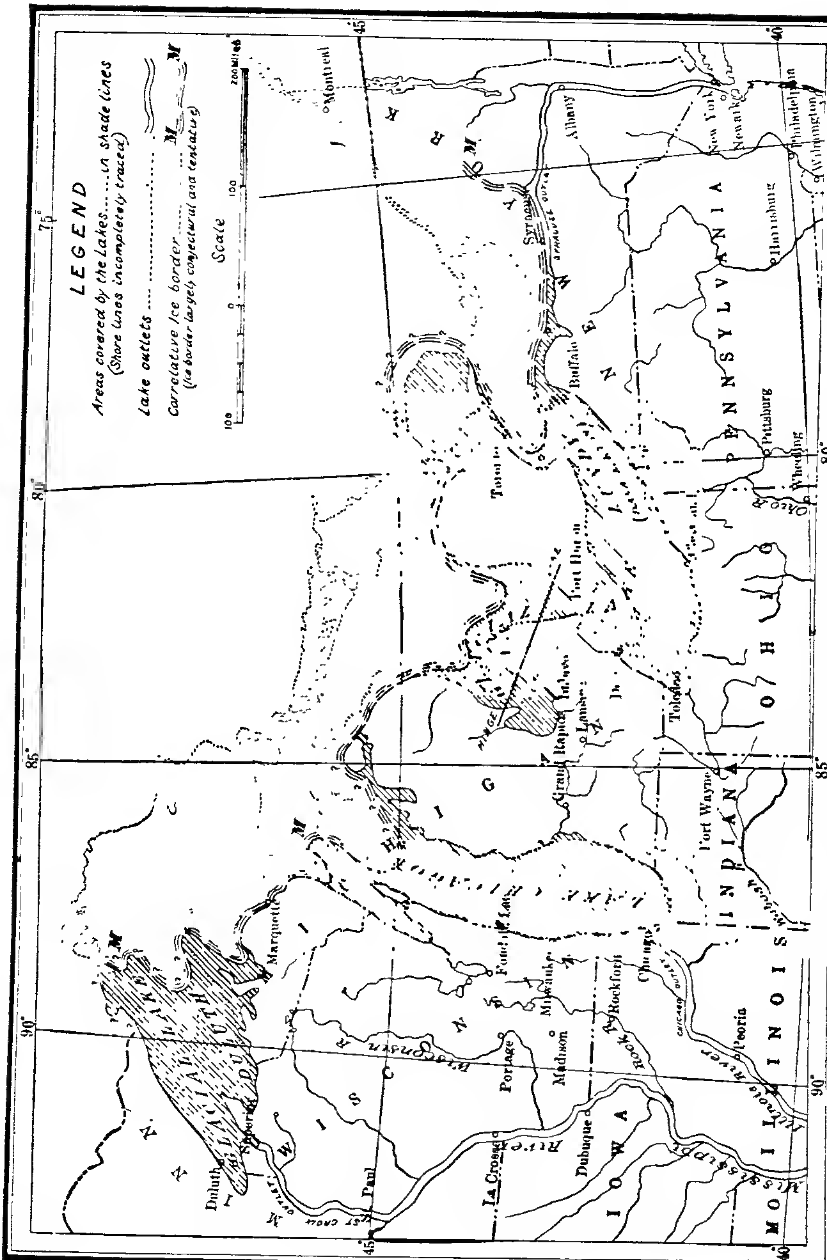



FIG. 345. Glacial Lakes Duluth, Chicago, and Lundy. Note the drainage of the western lakes into the Mississippi River, and the eastern lakes into the Hudson Valley. (After Taylor and Leverett, courtesy of The Smithsonian Institution.)

tinctly lower water level here than in the Erie Basin allowed the modern Niagara River to begin its history by flowing northward over the limestone plain near Buffalo. Meantime the waters of the upper lake basins had merged to form Lake Algonquin, which at first probably discharged past Detroit through the Erie Basin and into Lake Iroquois by way of Niagara River. Later, however, when the ice had withdrawn a little farther northward, a lower outlet was formed through the Trent River by which Lake Algonquin drained into Lake Iroquois. During the Algonquin-Iroquois stage the waters of all the Great Lakes

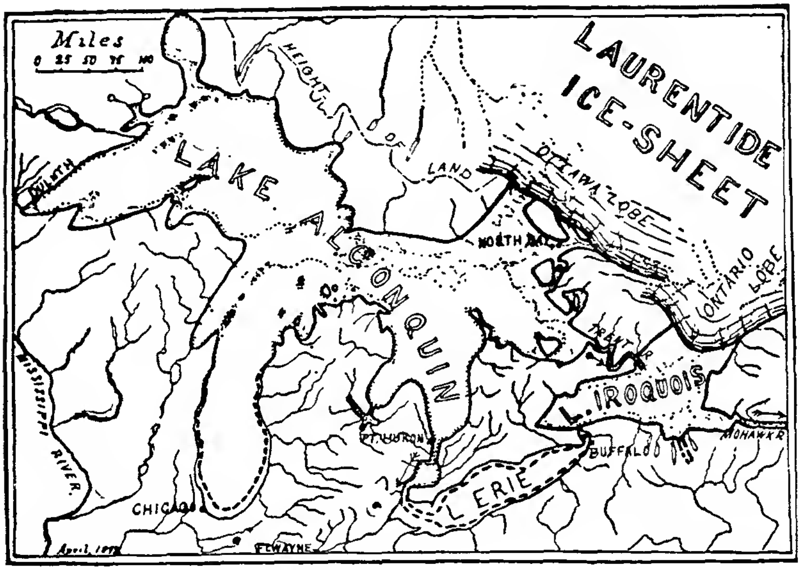



FIG. 346. The Algonquin-Iroquois stage of the Great Lakes, with outlet through the Mohawk-Hudson valleys of New York. (After Taylor, courtesy of the New York State Museum.)

region discharged through the Mohawk-Hudson valleys, and the volume of water which flowed through the Mohawk Valley must have been as great as, if not greater than, that which now goes over Niagara Falls. During this time the St. Lawrence Valley was still buried under ice.

Finally the ice withdrew far enough to free the St. Lawrence Valley when the waters of the Great Lakes region dropped to a still lower level, bringing about the Nipissing Great Lakes stage (see Fig. 347). The Nipissing Lakes found a low outlet through the Ottawa River (then

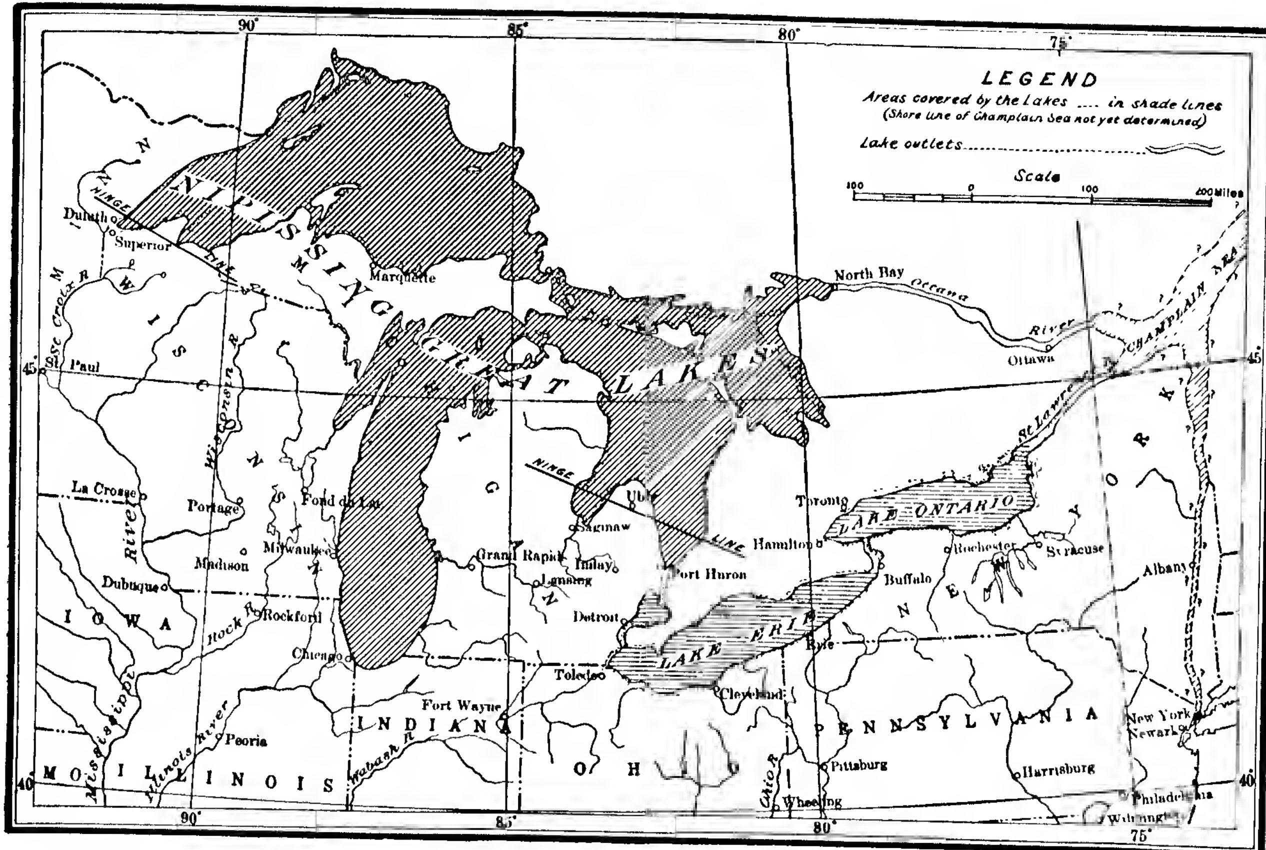



Fig. 347. The Nipissing Great Lakes and their correlatives. The oblique-lined area on the east was occupied by tide-water (Champlain Sea), but the boundary lines are not yet very definitely known. (After Taylor and Leverett, courtesy of The Smithsonian Institution.)

free from ice) and into the Champlain arm of the sea. Post-Glacial warping of the land brought the Great Lakes region into the present condition.

## Other Existing Lakes and Their Origin

Counting all, from the smallest to the largest, there are within the glaciated area of North America tens of thousands of lakes, and these constitute one of the most striking differences between the geography of the present and that of pre-Glacial time. These lakes are widely scattered, though in the United States they are most abundant in the regions of greater relief, such as Maine, New Hampshire, New York, and Minnesota, because lake basins were more readily formed by drift dams across the deeper pre-Glacial valleys of those regions.

It is well known that most of the larger lakes, especially those of the linear type, occupy portions of pre-Glacial stream channels. All the existing lakes are due, either directly or indirectly, to glacial action. Among the ways by which such bodies of water may be formed are these: (1) by building dams of glacial drift across old river channels; (2) by ice erosion; and (3) by accumulation of water in the numerous depressions which were formed by irregular deposition of the drift (kettle-holes, etc.). Hundreds of small lakes, often not more than mere pools in size, belong to the last named type, while very many of the large and small lakes are due chiefly to the existence of drift dams. Certain lakes in southeastern Canada and elsewhere appear to occupy rock basins scoured out by ice erosion.

## Extinct Glacial Lakes

The beds of thousands of extinct glacial lakes are known to be scattered over the glaciated area. Some of these existed only during the time of the ice retreat, while others persisted for a greater or lesser length of time after the Ice Age. Lakes Maumee, Iroquois, etc., already described, were fine examples of the first type. North-sloping valleys were particularly favorable for the development of glacial lakes during the retreat of the ice, because the ice front always acted as a dam across such valleys, thus causing the waters to become ponded. Among the best criteria for the recognition of these extinct glacial lakes are typical, flat-topped, delta deposits, formed by inflowing streams, and distinct beaches.

A fine example of a very large glacial lake in the interior of North America, and now represented only by remnants (e.g. Lake Winnipeg), has been called Lake Agassiz in honor of the discoverer of the fact of the Quaternary Ice Age. This lake, fully 700 miles long and several hundred miles wide, extended over the whole valley of the Red River of the North in North Dakota and Minnesota, and northward over much of Manitoba. It covered a larger area than the combined Great Lakes. Its water was held up by the united fronts of the Keewatin and Labradorean ice sheets as they retreated northward. Its outlet was southward through the Minnesota and Mississippi rivers until the ice melted back (northward) far enough to open the outlet by way of Nelson River to Hudson Bay, when the great body of water was rapidly lowered, leaving only the present-day remnants, principally Lake Winnipeg. The soil of this smooth old lake bed is wonderfully rich.

## Drainage Changes Due to Glaciation

In addition to its lakes, the glaciated area is also characterized by numerous gorges and waterfalls, which are largely due to glaciation. As a result of the very long time of pre-Glacial erosion, it is certain that typical, steep-sided, narrow gorges, as well as waterfalls, must have been very uncommon if present at all. Like lakes, such features are ephemeral, because, under our conditions of climate, gorges soon (geologically) widen at the top, and waterfalls disappear by retreat or by wearing away the hard rock which causes them.

Changes of stream courses are also numerous in many parts of the glaciated territory. It is the present purpose to describe only a few typical, well-studied cases of such stream changes. Even such large rivers as the Missouri and the Columbia were sometimes notably shifted out of their pre-Glacial channels by the invasion of the ice sheets. Thus, the Missouri River which formerly followed what is now the James River Valley in eastern South Dakota, was forced many miles westward to its present course across the state. The Cordilleran glacier filled a portion of the valley of the Columbia River in central Washington, forcing the mighty river eastward to find a new course for many miles, where it eroded a canyon called the Grand Coulee. On the melting of the ice, the river returned to its former valley.

The world-famous Niagara Falls and gorge are wholly post-glacial

in origin. After plunging 167 feet at the falls, the river rushes for 7 miles through the gorge, whose depth is between 200 and 300 feet. When the glacial waters in the eastern Great Lakes region had dropped to the Iroquois level, the Niagara limestone terrace in the vicinity of Buffalo and with steep escarpment or northern front at Lewiston and Queenstown, ceased to be covered with lake water, and the Niagara River came into existence by flowing northward over this limestone plain. The river first plunged over the escarpment at Lewiston, thus inaugurating the falls there. Since that time the falls have receded the 7 miles upstream to their present position. Soft shales underlie the layer of harder Niagara limestone, and the recession of the falls has clearly been caused by the breaking off of blocks of limestone due to undermining of the soft shales. A glance at the map (Fig. 348) will show that the gorge development is really taking place on the Horseshoe Falls side, where the volume of water is much greater, and that in a short time, geologically considered, the American Falls will be dry.

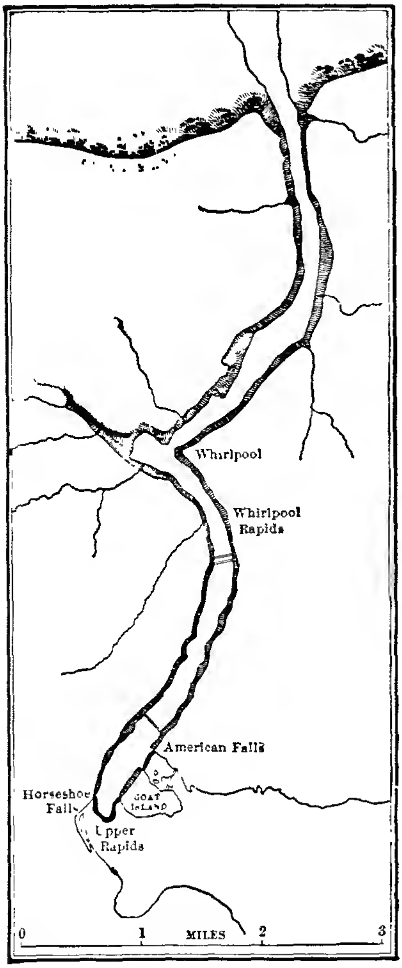



FIG. 348. Sketch map of the Niagara River gorge. (Modified after Gilbert, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

## CHANGES OF SEA LEVEL CAUSED BY THE GLACIATION

It has been estimated that the melting of the Antarctic glaciers, now covering about 5,000,000 square miles, would cause the level of the sea to rise fully 100 feet. When the greatest Pleistocene glaciers existed, and covered about 10,000,000 square miles, they represented

enough water temporarily removed from the sea to lower its level 250 feet or more. At such times the shorelines of the world were farther out than now, considerable parts of the present continental shelf areas then being land. During interglacial stages the sea level stood at about its present height, or higher by about 100 feet in case the glaciers completely melted away.

### Duration of the Glacial Epoch

According to Chamberlin and Salisbury, the most important criteria for estimating the duration of the Glacial epoch include: "(1) the amount of erosion of the drift; (2) the depth of leaching, weathering, and decomposition of its materials; (3) the amount of vegetable growth in interglacial intervals; (4) the climatic changes indicated by interglacial and glacial floras and faunas; (5) the times needful for the migration of faunas and floras, particularly certain plants whose means of migration are very limited; (6) the time required for advances and retreats of the ice; and some others." A few of these, as the first, are subject to direct measurement, but most of them are matters of judgment. Good estimates of the duration of the Glacial epoch range from 700,000 to 1,000,000 years or more.

### Length of Time Since the Glacial Epoch

Estimates of the length of time since the close of the Ice Age are perhaps more satisfactory, though it must be remembered that the close of the Ice Age was not the same for all places. The ice retreated northward very slowly and when, for example, southern New York was free from the ice, northern New York was still occupied by the glacier. The best estimates of the length of time since the close of the Ice Age are based upon the rate of recession of Niagara Falls. We have learned that Niagara River began its work about the time the glacial waters in the Erie-Ontario basins dropped to the Iroquois level, and that the falls were first formed by the plunging of the river over the limestone escarpment at Lewiston. Studies based upon actual surveys, drawings, daguerreotypes, photographs, etc., made between the years 1842 and 1905, have shown that the Horseshoe Fall had receded about 5 feet a year, while the American Fall, between 1827 and 1905, had receded about 3 inches a year. Thus the gorge cutting is clearly taking place on the Canadian side. The length of the gorge is 7 miles, and if we consider the rate of recession to have been always 5 feet a year, the length of time necessary to cut the gorge would be something over 7000

years. But the problem is not so simple, since we know that at the time of, or shortly after, the beginning of the river, the upper lakes drained out through the Trent River, and then still later through the Ottawa River. So it is evident that, for a good part of the time since the ice retreated from the Niagara region, the volume of water passing over the falls was notably diminished, and hence the length of time for the gorge cutting increased. The best estimates for the length of time since the ice retreated from the Niagara region vary from 10,000 to 40,000 years, an average being about 20,000 years. In a similar way, the time based upon the recession of St. Anthony's Falls, Minnesota, ranges from about 10,000 to 16,000 years. While closer estimates are practically impossible, it is at least certain that the time since the Ice Age is far less than its duration, and that, for the region of the northern United States, the final ice retreat occurred only a very short (geological) time ago.

When we consider the slight amount of weathering and erosion of the latest glacial drift, we are also forced to conclude that the time since the close of the Ice Age in the United States is to be measured by only some thousands of years. Thus kames, drumlins, extinct lake deltas, and moraines with their kettle holes, have generally been very little affected by erosion since their formation.

## Time Since the Climax of the Last Ice Sheet

A way to determine the number of years since the last (Wisconsin) ice sheet reached its climax is to find out how long it took the glacier to recede from its southernmost limit to Niagara Falls, or about 600 miles, and add this figure to the age of the falls.

A fair idea of the rate of recession of the last ice sheet may be gained by counting and correlating the layers of clay which were deposited in lakes in front of the retreating edge of the glacier. Each layer, consisting of a darker and a lighter band, is called a *varve*. Each varve represents the material laid down in one year, the lighter, coarser portion during the summer, and the darker, finer grained portion (colored with organic matter) during the winter. By the use of this method, De Geer found that the last ice sheet in Europe retreated a distance of 270 miles to the northwest of Stockholm in 5000 years, or at the rate of 285 feet per year. Antevs, using the same method, concluded that the last glacier receded a distance of 185 miles in western New England in 4100 years, or at the rate of 240 feet per year. If, therefore, we put the rate of retreat at about 260 feet per year, it took the Wisconsin ice

sheet somewhat more than 12,000 years to retreat from its southernmost limit to Niagara Falls. Combining this figure with the average estimate of 20,000 years for the age of Niagara, we get at least a rough approximation of the time since the last (or Wisconsin) glacier reached its climax, or about 32,000 years ago.

## Cause of the Glaciation

The cause of the glaciation has been a very perplexing problem. Various hypotheses, often of widely different character, have been offered by way of explanation, but there is nothing like general agreement on the subject. We have here a fine illustration of the difference between "fact" and "hypothesis" which the student of natural science must always keep clearly in mind. Thus, the fact of the Glacial epoch (including much of its history) is conclusively established, but the cause of the glaciation is a matter concerning which we have only hypotheses or speculations.

In this elementary work we can do no more than suggest several of the leading hypotheses. One point to be borne in mind is that no hypothesis is required to account for an average yearly temperature of more than 10 or possibly 12 degrees lower than at present over the glaciated area in order to have brought on the Ice Age. Another point is that both sufficient snowfall and low temperature were necessary.

**A Geologic (Elevation) Hypothesis.** As we have already pointed out, the evidence, chiefly from the submerged river channels along the Atlantic Coast, clearly indicates greater altitude of northeastern North America late in the Tertiary and probably also in the early Quaternary. An altitude several thousand feet greater than now has been claimed for this region. Since it is well known that the temperature becomes lower with increasing altitude (one degree for about 300 feet), it has been argued that the greater altitude of the glaciated area was in itself sufficient cause for the glaciation. "Northern elevation produced ice-accumulation; ice-accumulation by weight produced subsidence; subsidence produced moderation of temperature and melting of ice; and this last by lightening of load produced re-elevation" (J. Le Conte). It is not necessary to assume that maximum elevation and ice-accumulation were coincident, because an effect often lags behind its cause. This northern elevation also is believed to have sufficiently upraised the northern ocean basins to cut off warm currents, like the Gulf Stream, thereby depriving the northern lands of such warming influences.

It has been urged against this hypothesis that there is no positive evidence for nearly as much as several thousand feet of elevation of the glaciated region; that it is not at all proved that the northern elevation occurred at the proper time to produce glaciation; and that the only way glacial and interglacial stages could be accounted for would be by the unreasonable assumption of repeated elevation and subsidence corresponding to each advance and retreat of the ice.

**Chamberlin's Atmospheric Hypothesis.** Among the atmospheric hypotheses, the one which Chamberlin has put into its best form "is based chiefly on a postulated variation in the constituents of the atmosphere, especially in the amount of carbon dioxide and water. Both these elements have high capacities for absorbing heat, and both are being constantly supplied and constantly consumed. . . . The great elevation of the land at the close of the Tertiary seems to afford conditions favorable both for the consumption of carbon dioxide in large quantities, and for the reduction of the water content of the air. Depletion of these heat-absorbing elements was equivalent to the thinning of the thermal blanket which they constitute. If it was thinned, the temperature was reduced, and this would further decrease the amount of water vapor held in the air. The effect would thus be cumulative. The elevation and extension of the land would also produce its own effects on the prevailing winds and in other ways, so that some of the features of the hypsometric (elevation) hypothesis form a part of this hypothesis. . . . By variations in the consumption of carbon dioxide, especially in its absorption and escape from the ocean, the hypothesis attempts to explain the periodicity of glaciation. Localization (of glaciation) is attributed to the two great areas of permanent low pressure in proximity to which the ice sheets developed." [1]

**Huntington's Sunspot Hypothesis.** It seems to be a well-established fact that the temperature of the air near the earth's surface is lower at times of unusual sunspot activity. The intensity of sun's heat coming to the earth is known to vary as much as 3 to 5 per cent during short periods, ranging from a few days to a few weeks. Huntington has suggested that the several real glacial epochs of known geological time may have occurred during periods of exceptionally great and long sunspot activity, probably in combination with other factors. During such a cycle of very intense solar activity, not only would the earth's winds be stronger and hence conduct more heat upward from the earth's surface, but also these stronger winds would cause the great

[1] Chamberlin and Salisbury: *College Geology*, pp. 898–899.

eastward moving storm areas (or cyclonic storms) to travel farther north than they do at present in both North America and Europe. The lowering of the temperature and the increase in atmospheric moisture, resulting from the conditions just mentioned, would explain the gathering of the great Pleistocene glaciers.

**Volcanic Dust Hypothesis.** Strange as it seems, volcanic activity may be a contributing cause of glaciation. Volcanic dust from a great explosion is known to remain suspended in the atmosphere for many months. Dust in the atmosphere lowers the temperature of the earth's surface by keeping some of the sun's heat from reaching the earth. During a period of great activity of numerous volcanoes, the earth's surface temperature may be distinctly lowered, and it is perhaps significant that there was widespread, vigorous volcanic activity during the Pleistocene Ice Age.

**Conclusion.** In conclusion we may say that, as is true of so many other great natural phenomena, no one hypothesis or explanation is sufficient to account for all the features of glacial epochs. Probably several or all, or at least parts of several or all, of the above hypotheses must be properly combined in order to explain the phenomena of glaciation, and hence it is more readily understood why great glacial epochs have not been more common throughout the history of the earth.

## CHAPTER XXV

## CENOZOIC LIFE

### Plants

Vegetation had assumed a rather distinctly modern aspect well before the opening of the Cenozoic era, the great revolution from ancient to modern types having taken place about the middle of the Mesozoic era. During the Cenozoic, however, there was notable progress toward even more modern conditions, so that many genera became the same as now and gradually more and more present-day species were introduced.

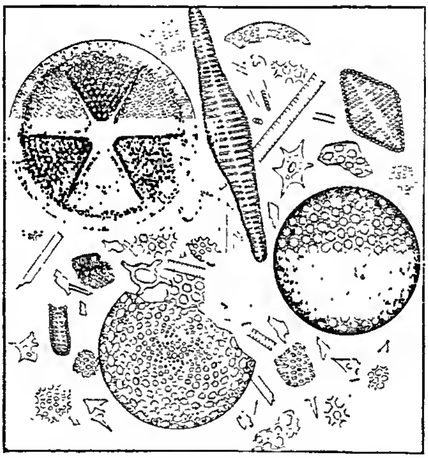


Fig. 349. Diatoms from diatomite of Miocene age at Lompoc, California. Very much enlarged. (After California State Mining Bureau.)

Among the simplest or single-celled plants, the *diatoms* deserve special mention. In certain times and places they swarmed in the Tertiary waters. "The microscopic plants which form siliceous shells, called diatoms, make extensive deposits in some places (Fig. 349). One stratum near Richmond, Virginia, is 30 feet thick and is many miles in extent; another, near Monterey, California, is 50 feet thick, and the material is as white and fine as chalk, which it resembles in appearance;

another, near Bilin in Bohemia, is 14 feet thick. . . . Ehrenberg has calculated that a cubic inch of the fine earthy rock contains about forty-one thousand millions of organisms. Such accumulations of diatoms, (called diatomite), are made both in fresh waters and salt, and in those of the ocean at all depths."[1]

During the earlier Tertiary, as we have learned, the climate of Europe and the northern United States was warm temperate to even subtropical and there flourished such trees as *palms, laurels, oaks, wil-*

FIG. 350. Two petrified tree stumps in upright position with roots in place. The bold outcrop in the background shows the nature of the volcanic fragmental material in which the trees were buried. Specimen Ridge, Yellowstone National Park. (After F. H. Knowlton, U. S. Geological Survey.)

*lows, chestnuts*, etc., with the addition of *magnolias, figs, poplars, ferns,* etc., in the western interior of the United States and southern Canada. As far north as Greenland and Spitzbergen, there were forests with *maples, camphor trees, figs, laurels, cypresses, poplars,* and *sequoias.* The sequoias, which are of special interest, began in the Late Jurassic; attained their culmination in numbers and species in the Tertiary; and are now represented by only two species,—the so-called "big trees" and the redwoods,—which are almost wholly confined to

[1] J. D. Dana: *Text-book of Geology*, 5th ed., pp. 391–393.

California. During the Tertiary they ranged from Greenland on the north to New Zealand on the south, often in great forests.

Many of the present-day forest plants of Central America and northern South America, particularly in the "rain forest" of the Venezuelan Andes, greatly resemble those which lived in western North America during Early and Middle Tertiary times. As the Cenozoic climate gradually became cooler and drier, these plants were driven southward into warmer and moister regions in order to survive. For such a reason, the palms, figs, and magnolias disappeared from the western interior of North America, and the palms from Europe.

Fine examples of Tertiary (Miocene) warmer climate trees, including sycamores, laurels, oaks, pines, and sequoias, are remarkably preserved in petrified form in Yellowstone National Park (Fig. 350). A dozen or more so-called "petrified forests" occur there at different horizons through a thickness of about 2000 feet of nearly horizontal beds of fragmental volcanic rocks. Parts of many petrified tree-trunks, with roots in place, are still in upright position where they grew. These are remains of successive forests which were killed and buried by showers of eruptive fragments, then petrified, and since partly exposed by erosion.

In the Tertiary both *grasses* and *cereals* became abundant and they must have had an important influence in the development of the principal groups of herbivorous mammals.

## Animals

Since the Tertiary invertebrates were in nearly every way so similar to those of today, we shall give special attention to only a few features of interest.

Among **protozoans,** the *foraminifers* were exceedingly abundant and often remarkable for their great size. Of these the *Nummulites*, so-called because coin-shaped, form great limestone deposits in the Old World Eocene. They attained a diameter as great as half an inch to an inch.

**Porifers, cœlenterates, echinoderms, and molluscoids** were almost wholly modern in character, with crinoids and brachiopods both rare.

Among **mollusks** both *pelecypods* (Fig. 351), and *gastropods* were exceedingly common, perhaps more so than ever before, and of very modern aspect (Fig. 352). *Oysters* appear to have reached their culmination in size at least, some having grown to a length of ten to twenty inches and a width of six or eight inches (Fig. 351). Pelecypods are

important Tertiary horizon markers (Fig. 352). *Cephalopods*, as we have learned, diminished remarkably at the close of the Cretaceous, the great groups of the *ammonites* and *belemnites* having disappeared, while the *nautiloids* (e.g. Nautilus) were more diversified and wide-spread than now. The *dibranchs* were of the modern squid and cuttle-fish types.

Among **arthropods** all the principal groups except the simplest (e.g. trilobites and eurypterids) were represented, the *crabs* among the *crus-*

FIG. 351. Large oyster shells, *Ostrea georgiana*, in Eocene strata of Georgia. (After L. W. Stephenson, Geol. Sur. Ga., Bul. 26.)

*taceans* having become numerous and varied. *Insects* are known in far greater numbers and variety than from any preceding period. All the important groups or orders were represented, including the highest, such as moths, butterflies, beetles, bees, and ants. The prolific vegetation of the period was of course very favorable for insect development.

In a single Miocene stratum a few feet thick at Oeningen, near the Swiss border, more than 900 species of insects have been found.

Another remarkable occurrence of fossil insects is in the amber of northern Germany, especially on the shores of the Baltic Sea, where fully 2000 species have been obtained. The amber is a fossil resin of early Oligocene age derived from certain conifers. The insects were caught in the resin while it was still soft and sticky and they have been

perfectly preserved in outline forms (as molds) to the present day in the often quite transparent amber.

At Florissant, Colorado, certain fresh water shales of Miocene age are said to be black with the remains of insects. Over 2000 species are

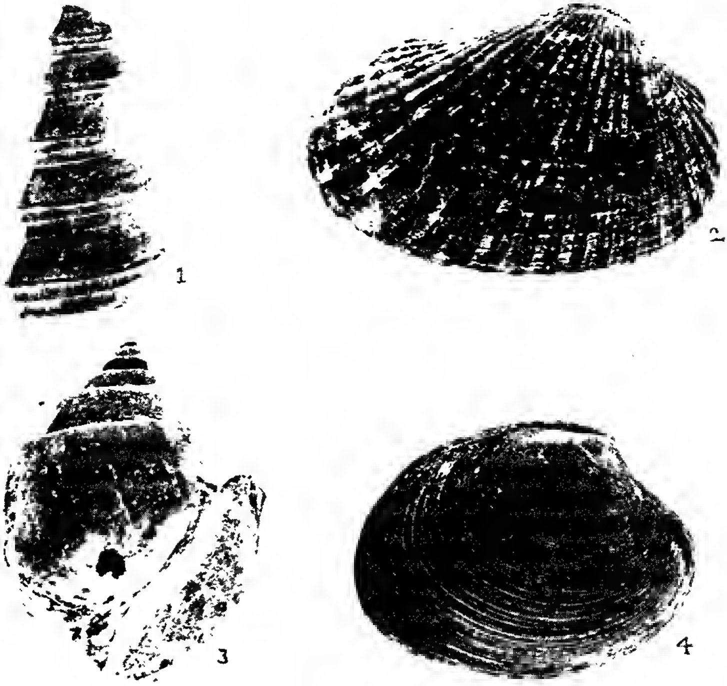



Fig. 352. Pacific Coast Tertiary index-fossil mollusks. *1*, a Miocene gastropod, *Turritella temblorensis* (Wiedey); *2*, a Pliocene pelecypod, *Anadara trilineata*, variety calcarea (Grant and Gale); *3*, an Eocene gastropod, *Pachycrommium inezanum* (Conrad); *4*, an Oligocene pelecypod, *Pitar dalli* (Weaver). All × ⅔. (Photo by C. D. Redmond.)

represented as well as various plants, fishes, and even a bird with well-preserved feathers.

**Fishes.** These were in general much like those of the later Mesozoic, though even more modern in aspect. *Teleosts* (Fig. 353) predominated, but *sharks* were abundant and of great size—60 to 80 feet long—with fossil teeth up to 5 or 6 inches long occurring in immense numbers in some places as, for example, the Gulf Coastal Plain of the United States.

**Amphibians.** After their great development in the late Paleozoic, the amphibians never again assumed much importance. In the Cenozoic they were represented only by such modern types as salamanders, frogs, and toads.

**Reptiles.** These, too, were quite modern in character, with lizards, snakes, crocodiles, and turtles all common and varied.

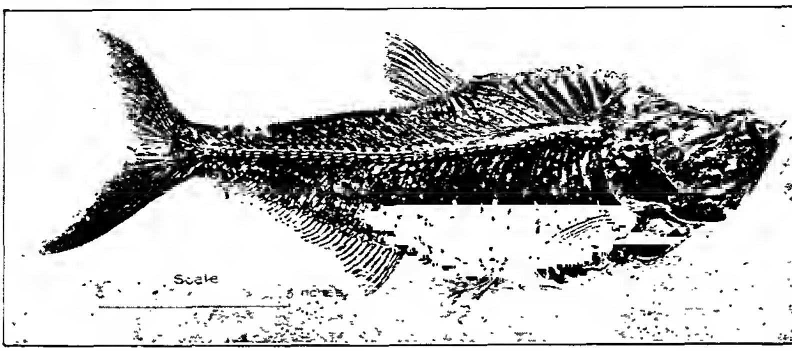


FIG. 353. A nearly perfect fossil teleost fish, *Diplomystus densatus*, from the Eocene of Wyoming. (After Veatch, U. S. Geological Survey, Prof. Paper 56.)

**Birds.** These were much more advanced and numerous than in later Mesozoic time, and many of the modern groups had representatives. A few of the more primitive or generalized types, however, still existed in the Early Tertiary. Thus a toothed bird has been found in the Eocene of England, though it is to be noted that the teeth were only dentations of the edge of the bill (Fig. 354). With rare exceptions, modern birds are entirely toothless. Another special feature was the existence of very large, flightless ostrich-like forms which attained heights up to fully 10 feet. One kind laid eggs more than a foot long.

FIG. 354. Head of an Eocene bird, *Odontopteryx toliapicus*, showing teeth. (After Owen.)

**Mammals (except Primates).** *General Statement.* All during the Mesozoic era mammals existed, but they were represented only by comparatively few, small, primitive forms, and they always occupied a very subordinate position in the animal world. They were kept in obscurity by the dominant and diversified reptiles. The mighty crustal disturbance of late Mesozoic time, reaching a grand climax in the Rocky Mountain Revolution, left in its wake the end of the reign of reptiles,

and the beginning of the rule of the highly organized mammals. Very early in the Tertiary there began a wonderful development of mammals. Evolution of many of the higher groups went on rapidly, so that by the close of the period the mammals had become differentiated into most of the principal modern types. One of the most significant features in the evolution of the mammals during the Cenozoic was the gradual increase in the relative sizes of the brains. The accompanying sketches graphically illustrate this fact (Fig. 355).

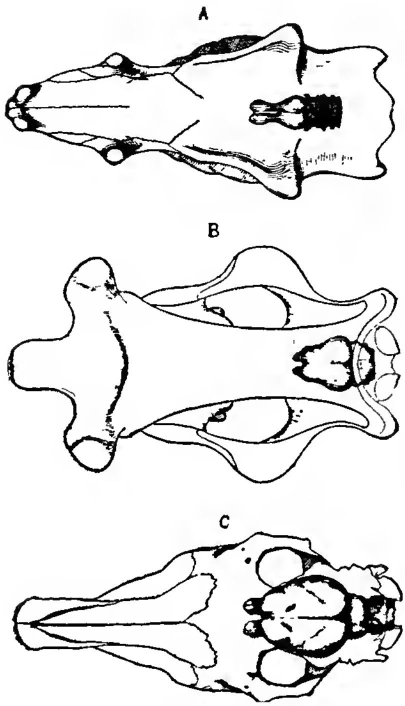



FIG. 355. Sketches to illustrate increase in size of brains of mammals from the Eocene to the present. *A*, Eocene *Uintatherium*; *B*, Miocene *Brontotherium*; *C*, modern horse, *Equus*. (After Marsh, from Shimer's "Introduction to the Study of Fossils," courtesy of the Macmillan Company.)

With the exception of a few very primitive, Late Cretaceous, insectivorous, placental mammals, only monotremes and marsupials existed during the Mesozoic, but during the Tertiary they were very subordinate to the placentals, and today they are comparatively rare. The Cenozoic was (and is), therefore, very decidedly the "Age of Placental Mammals."

Because of the great wealth of available material concerning Cenozoic mammals, we can do no more, in our brief survey, than to describe some typical examples of the most interesting and better known forms, with emphasis upon evolutionary changes shown by them.

*Generalized Mammals of the Eocene.* Although mammals were the dominant animals even in the Early Tertiary, nevertheless they were not then differentiated into the more or less clearly defined groups of today such as the *carnivores*, or flesh eaters (e.g. dogs, bears, tigers, etc.); *perissodactyls*, or hoofed mammals with an odd number of toes (e.g. horses, rhinoceroses, etc.); *artiodactyls*, or hoofed mammals with an even number of toes (e.g. camels, deer, pigs, etc.); *proboscidians*,

or trunk-bearing hoofed mammals (e.g. elephants); *rodents*, or gnawers (e.g. rats, squirrels, etc.); *insectivores* (e.g. moles, hedgehogs, etc.); *cetaceans*, or exclusively swimmers (e.g. whales, dolphins, etc.); *primates*, or the very highest of all mammals (e.g. monkeys, man, etc.); and many others. These groups, traced back toward the Early Tertiary, gradually become less and less distinct until, in the Eocene, they cannot be at all distinguished as separate groups, but rather we find ancestral or generalized forms which show combinations of features of the later groups.

FIG. 356. A nearly perfect skeleton of the Eocene *Phenacodus primaevus*. (After Cope.)

One of the most characteristic of these generalized types of the Early Eocene was *Phenacodus* (see Fig. 356). The various species of this genus showed about the same range in size as modern dogs. Each foot had five toes which were supplied with nails rather between true claws and true hoofs in structure. The simple (primitive) teeth indicate that the animal was omnivorous, that is, both plant and flesh eating. In harmony with other Early Tertiary mammals, the brain was relatively small and almost devoid of convolutions, thus pointing to a low grade of mental development.

*Perissodactyls* (e.g. horse). As an example of the history of the odd-toed, hoofed mammals, we shall consider the well-known evolution of the *horse* family. At least forty species of this family, ranging from Early Eocene to the present, have been described, and practically every connecting link in the evolution of the family is known. Only a few of the most important changes can be noted in our brief description, which is, in fact, not much more than an explanation of the excellent chart shown in Fig. 357. The earliest form, called *Eohippus*, occurring in the lower Eocene, was about the size of a large cat (Fig. 358). On the forefoot it had four functional toes (one larger than the others) and a splint or imperfectly developed fifth toe. The hind foot had three functional toes and a splint. Doubtless this early member of the horse family was derived from an original five-toed ancestor whose general structure was something like Phenacodus. In the later Eocene *Protorohippus* had four distinct toes on the front foot and three on the hind foot, but with no sign of splints. This form was but little larger than Eohippus. During the Oligocene *Mesohippus* had three functional toes

(the middle one being distinctly larger), with the former fourth toe reduced to a splint on the front foot, while the three functional toes continued on the hind foot. It was about the size of a sheep. In the Miocene *Protohippus* had three toes on both fore and hind feet, but in each case only one was large and functional, with the other two small toes not long enough to reach the ground. This form was about the size of a pony. During the Pliocene and Quaternary, *Equus*, or the modern horse, had, and has, one toe only on each front and hind foot

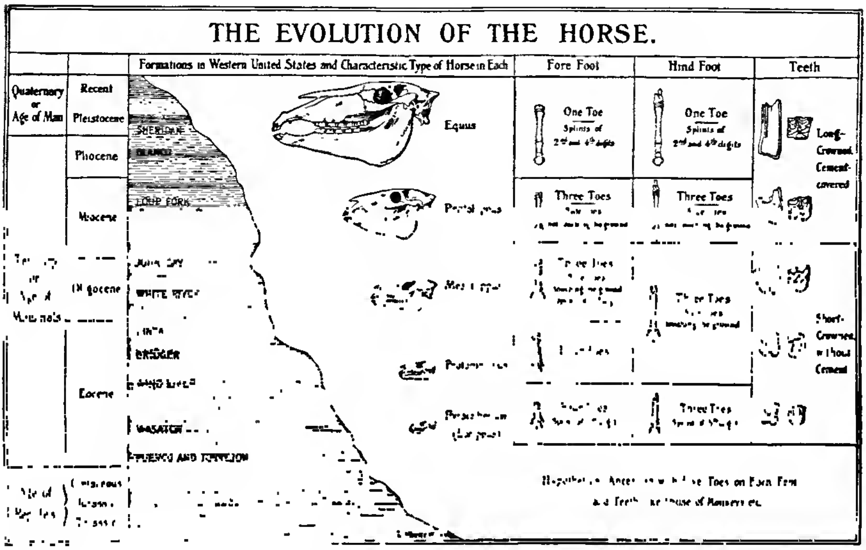



FIG. 357. Chart to illustrate the evolution of the horse family. (After W. D. Matthew, *Amer. Mus. Nat. Hist. Journal.*)

with the two side toes of Protohippus reduced to mere splint bones, entirely non-functional. Thus we see that the middle toe of the original five-toed ancestor has developed, to the exclusion of the others, and it is thought that this has tended toward greater fleetness of foot. While these evolutionary changes took place, there were also gradually developed longer and more complex teeth; the two entirely separate bones (radius and ulna) of the fore limb gradually became consolidated into a single strong bone; and the brain steadily increased in relative size.

*Artiodactyls* (e.g. camel). These even-toed, hoofed mammals, like the odd-toed ones, were descended from a five-toed Eocene ancestor. In their development the first toe disappeared, while the middle pair of the

remaining four became larger and the two side toes became smaller and smaller, having disappeared altogether in such a type as the modern camel. This sort of evolution in the camel family has been traced in

FIG. 358. Primitive or ancestral horses, *Eohippus*, of the Eocene. Restored by C. R. Knight under the direction of H. F. Osborn. (Permission of American Museum of Natural History.)

almost as much detail as in the horse family. Beside the camel, other two-toed existing forms are deer, cattle, and sheep. The two-toed artiodactyls now predominate, while the four-toed forms (at present represented e.g. by hogs and hippopotami) culminated in the Tertiary.

*Proboscidians* (e.g. elephant). This group of hoofed mammals, characterized by the proboscis (trunk), has been traced through many intermediate forms back to primitive Eocene ancestry. Proboscidians culminated in the Pliocene, when they were the largest (up to 13 or 14 feet high), the most numerous, and widespread over much of the earth except Australia. *Mastodons*, now wholly extinct, are charac-

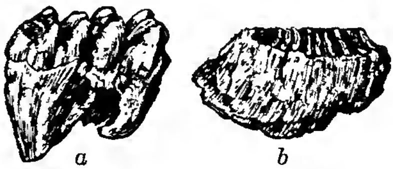



FIG. 359. *a*, mastodon tooth; *b*, mammoth tooth. Both viewed from the side.

terized by having knoblike prominences on the chewing surfaces of their large teeth (Fig. 359*a*), while the true *elephants* (including the extinct *mammoths*) have large, nearly flat grinding surfaces on their teeth (Fig. 359*b*). True elephants also nearly always show greater curvature of the tusks. The mammoth had long brown hair.

The accompanying sketches (Fig. 360), together with the following excellent summary by Lull, will give a good idea of the evolution of the proboscidians. "Increase in size and in the development of pillar-like limbs to support the enormous weight. Increase in size and complexity of the teeth and their consequent diminution in numbers and the development of the peculiar method of tooth succession. The loss of the canines and of all of the incisor teeth except the second pair in the upper and lower jaws and the development of these as tusks. The gradual elongation of the symphysis or union of the lower jaws to strengthen and support the lower tusks while digging, culminating in *Tetrabeledon* (or *Gomphotherium*) *angustidens*. The apparently sudden shortening of this symphysis following the loss of the lower tusks and the compensating increase in size and the change in curvature of those of the upper jaw.

"The increase in bulk and height, together with the shortening of the neck necessitated by the increasing weight of the head with its great battery of tusks, necessitated the development of a prehensile upper lip which gradually evolved into a proboscis for food gathering. The elongation of the lower jaws implies a similar elongation of this proboscis in order that the latter may reach beyond the tusks. The trunk did not, however, reach maximum utility until the shortening jaw, removing the support from beneath, left it pendant, as in the living elephant."

During Quaternary time the *proboscidians* were well represented by both the *mastodons* and the *mammoths*. These were smaller than those of the Late Tertiary or about the size of modern elephants. "During Pleistocene times the Proboscidia covered all of the great land masses except Australia, but were diminishing in numbers, and toward the close of the Pleistocene the period of decadence began, resulting in the extinction of all but the Indian and African elephants of today" (Lull). The mastodon roamed only over much of North America and part of South America, having become extinct in the Old World in the Late Tertiary. The mammoth had a much wider range from the Atlantic states to Alaska; across Siberia; through central Europe; and even to

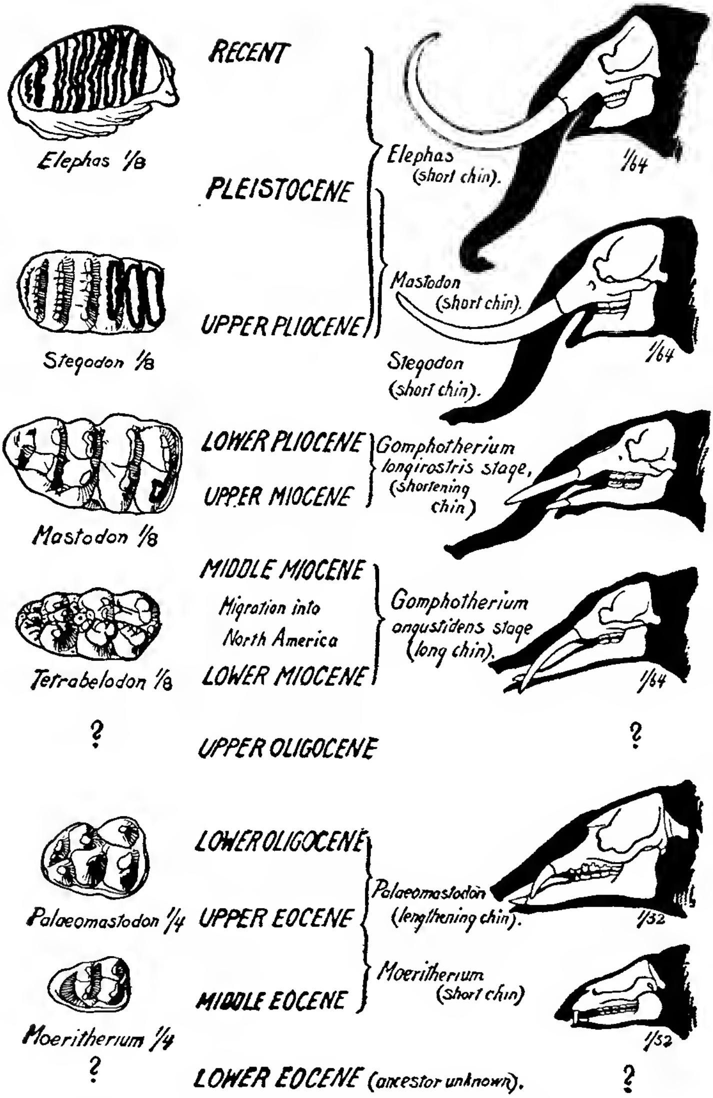



FIG. 360. Chart to illustrate the evolution of the elephants. (From Scott, after Lull, modified by Sinclair, by courtesy of the Macmillan Company.)

the British Isles. Fine examples of the almost perfect preservation of entire organisms of now extinct forms are furnished by specimens of frozen mammoths which have been in nature's "cold storage" for thousands of years in the gravels or ice of Siberia. In several cases much of the hide, long brown hair, and even the flesh are known to have been perfectly preserved, the flesh having been eaten by dogs or even the natives themselves. Two of the finest specimens were discovered in 1806 and 1901.

*Carnivores* (tigers, dogs, etc.). These modern flesh-eaters can be traced back to a generalized order or group (so-called *creodonts*), which had certain characters suggesting the insect-eaters, hoofed mammals, and marsupials, as well as the carnivores. These creodonts or ancestral flesh-eaters had small, simple brains and many small teeth. In the course of evolution the existing carnivorous families have been derived from them.

*Rodents* (rats, porcupines, squirrels, etc.). The rodents (gnawers) can be traced back to the Early Eocene, when the incisor teeth were just developing a structure suitable for gnawing. By the middle of the Eocene the rodents were common and their incisors were highly specialized for gnawing. Primitive squirrel-like forms are known from the Late Eocene. Certain Pleistocene rodents were 5 feet long.

*Insectivores* (e.g. moles, hedgehogs, etc.). These have also been traced back to the Eocene, and, like the rodents, they still show many of their ancestral or primitive features. They have changed much less than most of the other classes of mammals.

Among the *edentates* (sloths, armadillos, etc.), which belong to the simplest placental mammals, the *Megatherium* and the *glyptodonts* are of special interest. The former, a sort of giant groundsloth, was remarkably massive and attained a length of 15 to 18 feet. Its thigh bones were two or three times the thickness of those of the elephant, and its front feet were about a yard long. The tooth structure shows it to have been a plant feeder. This powerful creature could easily have toppled over small trees in order to strip off the leaves. The glyptodonts (see Fig. 361) were giant armadillos up to 8 feet long and armed with a very strong turtle-like carapace. These edentates, including many species, were common in South America and in North America as far north as Pennsylvania and Oregon.

*Cetaceans* (e.g. whales, porpoises, etc.). In our study of Mesozoic reptiles we found that certain forms took to the sea and became marine fishlike creatures, such as the ichthyosaur and the mosasaur. So in the

Tertiary (even in the Eocene) certain mammals became so adapted to the water environment as to become fishlike forms, such as whales, porpoises, etc., which are often popularly regarded as true fishes. Apparently we have here an example of retrogression in evolution, because true land animals took to the water and their legs degenerated into swimming paddles. Certain whalelike forms (zeuglodons) of the Eocene reached lengths up to 60 or 80 feet and must have been extremely

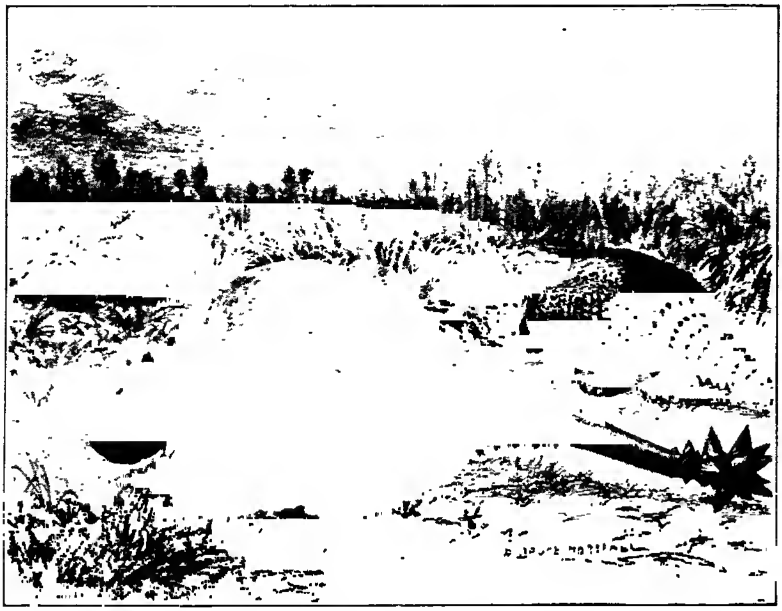


FIG. 361. Great armored glyptodonts, *Doedicurus clavicaudatus* and *Glyptodon clavipes.* (After W. B. Scott, by permission of the Macmillan Company.)

abundant, their vertebræ often being found in great numbers in Alabama and other places.

*Pleistocene Bones in Asphalt.* Fossil bones in a wonderful state of preservation, occurring under unique conditions, have been found in great numbers in the so-called La Brea tar and asphalt deposits in Los Angeles. The tar and asphalt are oxidized petroleum which has been oozing upward to the surface along a fracture in the earth's crust since Middle Pleistocene time. The animals lost their lives by becoming trapped in the tar pits. Among the many kinds of now extinct animals represented in fossil condition are great *elephants, saber-toothed tigers, giant ground-sloths, bisons,* and *birds.*

**Distribution of Quaternary Plants and Animals.** *Effects of Glaciation.* The alternations of glacial and interglacial climates caused corresponding migrations of colder and warmer climate animals and plants. While a great ice sheet was advancing, Arctic animals and plants ranged farther and farther southward even into what are now temperate latitudes. Thus the *musk-ox* ranged southward to Iowa and Kentucky, and the *walrus* to Virginia, while in Europe the *reindeer, Arctic fox*, etc., ranged southward into France. During the retreat of a great ice sheet, the Arctic fauna and flora retreated to colder climatic conditions, either by following the ice front northward or by going up the mountains as they were freed from the ice. This retreat up the mountains affords a ready explanation of the fact that certain Arctic plants and animals (especially insects) are now found, in the Alps and higher parts of the White Mountains of New Hampshire, separated from their former habitat by many hundreds of miles of climate now too mild for them to cross.

*Effects of Diastrophism.* During the Pleistocene, the geographical environment favored a very widespread distribution of mammals over most of the land areas. Thus North America and South America were connected; North America and Asia were joined across what is now the Bering Sea; and Eurasia and Africa were well connected. Australia was, and had been for a long time, one of the largest isolated land masses, and herein lies the explanation of its most peculiar fauna and flora. For example, of the many known species of mammals all are non-placentals, that is, they are monotremes and marsupials. Non-placentals inhabited most of the great land areas (including Australia) during the Mesozoic era. Since true placental mammals made their appearance in the Early Tertiary, it is quite certain that Australia was isolated from the Asiatic continent before the Tertiary and that under the more local conditions and less severe struggle, placentals were never evolved there and they never got there from other continents, except as artificially introduced by man in Late Quaternary time.

Madagascar also has a mammalian fauna very peculiar to itself. This island was separated from the mainland before Quaternary time, and its mammals, because of less severe struggle for existence, have changed more slowly and in their own way as compared with those of the African continent.

The coast islands of southern California show similar relation to the mainland, but more especially as regards the plant species.

**Primates (except Man).** The *primates* comprise the highest and most complex group of all animals. There are two main divisions—the *lemuroids*, including *lemurs* and *tarsius;* and the *anthropoids*, including monkeys, apes, and man. Primates are comparatively uncommon in fossil form because they were never numerous like many other animals, and because they were land animals, usually living in trees. Conditions for their fossilization were, therefore, seldom favorable. During the last 75 years, however, so many fossil primates have been found that we are now able to outline the main steps in the general evolution of the primates (including man) from the Early Eocene to the present.

The oldest known true primates—the lemuroids—date from the Eocene, and they represented the lowest stage or type of all known primates. Both the lemurs, with descendants now living in Madagas-

FIG. 362. A lemur from Madagascar. It is a living representative of the very primitive Eocene primates. (After Beddard.)

car, and the Tarsius, with present-day descendants in the East Indies, existed in the Eocene.

From Oligocene strata we have records of the most primitive anthropoids or anthropoid-like primates, including both primitive or ancestral monkeys and apelike creatures.

Many species of true anthropoids (both monkeys and apes) existed during both the Miocene and Pliocene epochs, as proved by the fossils found in widely separated parts of the world. Various species have of course ranged to the present time.

**Geologic History of Man.** *General Statement.* Thus far we have said little about the interesting and important subject of man's first appearance, and nothing about his early history. Since man, who represents the very highest type of organism which has ever inhabited the earth, belongs to one of the most recent and important groups of animals, it is appropriate that a brief discussion of his origin and early

history be reserved for the very last. Up to the present, at least, progressive organic evolution through hundreds of millions of years has reached its climax in man.

Because of additional discoveries and better methods of study, our knowledge of prehistoric man is becoming more satisfactory year by year. The ablest students of the subject have agreed upon several important points, while regarding others there is still much disagreement. There is quite a general agreement (1) that man has evolved from lower forms of primates; (2) that there are clearly recognizable at least two types or species of true man, namely, (a) *Homo primigenius* (Middle Quaternary), a primitive type now extinct, and (b) *Homo sapiens* (Late Quaternary), represented by existing man; (3) that true man certainly existed during the Pleistocene; (4) that, on a most conservative basis, true man was on the earth no less than 200,000 years ago; and (5) that there is no positive evidence for the existence of true man earlier than the Pleistocene or Glacial epoch.

Difference of opinion commonly surrounded such as: (1) The classification of the early ancestral forms, that is whether they should be called apes, manlike apes, or apelike men; and (2) the portions of the Quaternary system represented by the deposits in which man's bones or implements are found, or by the remains of animals found associated with man's bones or implements.

Bones and implements of ancient man, and his early ancestral forms, are found chiefly in river gravels, loess, caves, and interglacial deposits.

The following tabular arrangement is introduced in order to graphically represent (synoptically) certain of the most significant features in connection with the geologic history of man. It should be clearly borne in mind that, in some respects, these are only tentative arrangements, though they do summarize our most recent knowledge based upon the work of able students of the subject.

*Manlike Apes.* Among the most ancient known remains of man's early ancestral forms (manlike apes), five of special interest and importance will be described. These are all of greater antiquity (Early Pleistocene) than any bones of what are considered to be true human beings. It should, however, be emphasized that there is no sharp line of demarcation between fossil manlike apes and man, but rather there are transitional or gradational forms.

*Australopithecus*, or the so-called "southern ape," lived in South Africa. A skull and jaw bones were found in 1925 buried in a cave deposit along with remains of various extinct animals of Early Pleisto-

CHRONOLOGICAL TABLE OF MAN AND HIS ANCESTORS

| *Geologic Age* | | *Estimated Time Ago* | *Cultural Age* | | | | *Fossil Forms* |
|---|---|---|---|---|---|---|---|
| Post-Glacial or Recent epoch | | | Historic age | Iron and bronze work | | Homo sapiens | Modern |
| | | | Neolithic age | Well-shaped and polished stone implements | | | |
| | | 20,000 years | | | | | |
| Pleistocene or Glacial epoch | Fourth glacial stage | | Paleolithic age | Magdalenian<br>Solutrean<br>Aurignacian | More or less well-formed stone implements | Homo sapiens | Crô-Magnon |
| | Third interglacial stage | | | Mousterian | | Homo primigenius | Neanderthal |
| | Third glacial stage | 150,000 years | | Acheulian | | | |
| | Second interglacial stage | | | Chellean | | | |
| | Second glacial stage | 500,000 years | Eolithic age | | | Manlike apes | Piltdown |
| | First interglacial stage | | | Pre-Chellean | Very rough stone implements | | Heidelberg<br>Peking |
| | First glacial stage | | | | | | Java<br>Australopithecus |
| Pliocene epoch | | 1,000,000 years | No known implements | | | | Apes |

cene or Late Pliocene age. The creature was an ape, but more advanced than any living ape. He represented a very old, low type of the manlike apes (Fig. 363).

*Pithecanthropus erectus,* also known as the "Java man," was discovered in 1891. Parts of a skull and lower jaw, several teeth, and a thigh bone were found buried under considerable sediment. Associated with the remains were various bones of extinct animals of Early Pleistocene age. The exceptionally thick skull is plainly apelike with narrow, low forehead, and very massive, prominent brow ridges. The teeth were of rather human structure, but they projected strongly in front. The creature had a protruding mouth and practically no chin, as in the apes. The size of the brain was considerably less than that of lower forms of true man. Pithecanthropus represented a very old, low type of the manlike apes (Fig. 364).

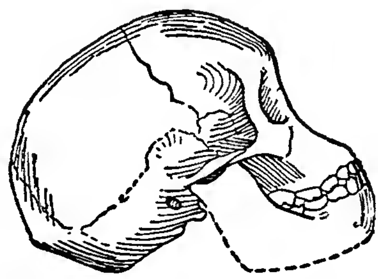


FIG. 363. The head of *Australopithecus,* or the "southern ape." (After Broom.)

*Sinanthropus pekingensis,* often called "Peking man," was discovered in 1928-29 near Peiping, China. A skull, two jaws, teeth, and skull fragments were found buried in a cave deposit. The thick-boned skull shows a low, receding forehead, receding chin, massive brow ridges, and

a wide, comparatively flat nose. The brain capacity was intermediate between Pithecanthropus and lower forms of true man. Many crude stone implements were associated with the remains. Charcoal buried with the bones shows that "Peking man" knew the use of fire. Various associated bones of extinct animals proves the Early Pleistocene age of the creature.

*Paleoanthropus heidelbergensis,* or so-called "Heidelberg man," is represented only by a well preserved jaw with teeth. It was buried under 70 feet of sediment near Heidelberg, Germany. The jaw is very massive (apelike) with practically no chin, but the teeth are of human structure. It is definitely of Early Pleistocene (first interglacial) age as shown by directly associated bones of other animals of that age.

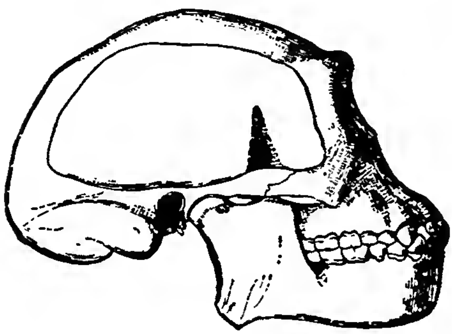


FIG. 364. Restoration of the head of *Pithecanthropus erectus.* (After Du Bois, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

*Eoanthropus dawsoni,* or "Piltdown man," is represented by most of a skull and teeth found during 1911-12 and 1917 at Piltdown, England. The remains were accompanied by Eolithic flints and bones of certain extinct animals of rather Early Pleistocene age. The jaw, the absence of a distinct chin, the unusually thick skull, and the fairly massive brow ridges are strongly apelike, but the teeth are notably human. Eoanthropus had a brain larger than that of any ape and equal to that of lower man. It was, therefore, exceptionally large for such an old form. The creature represented a later, distinctly human type of the manlike apes. Associated charcoal and burnt flint implements proves that he used fire.

Summarizing the characteristics of the manlike apes, W. H. Duckworth says: "Evidence exists in each case to the effect that far-distant human ancestors are hereby revealed to their modern representatives. Of their physical characters, distinct indications are given of the possession of a small brain in a flattened brain-case associated with powerful jaws and massive continuous brow-ridges; the lower part of the face being distinguished by the absence of any projection of the chin. The teeth indicate with some degree of probability that their diet was of a

mixed nature, resembling in this respect the condition of many modern savage tribes. . . . Whether they habitually assumed the distinctive erect attitude is a point still in doubt. . . . It is probable that in stature they were comparable, if not superior to, the average man of today."

*Paleolithic Man.* The oldest form of primate which, by rather common agreement, is considered to have represented true man appeared in about the middle of the Pleistocene epoch. Many examples of imple-

*a* *b* *c*

Fig. 365. Comparison of skulls: *a*, modern chimpanzee; *b*, Paleolithic man; *c*, modern Frenchman. (After E. Rivet, from New York State Museum Bulletin 173.)

ments and bones of Middle and Late Pleistocene (or Paleolithic) man have been found within and without the glaciated area of Europe. It is often difficult to be sure of the precise glacial or interglacial stage to which given specimens belong. Their Pleistocene age is, however, certain as shown by the conditions under which they have been found. Thus the bones or implements have often been found buried at considerable depths in sediments which have not been disturbed since their deposition, or in direct association with the remains of extinct Pleistocene animals such as the mammoth, cave bear, cave hyena, woolly rhinoceros, reindeer, musk ox, etc.

The Middle and Late Pleistocene men are called Paleolithic ("old stone") because they are known to have fashioned many rude to well-shaped stone implements. That Paleolithic man hunted the wild beasts of his time is certain because of the direct and frequent association of his bones and hunting weapons with the bones of contemporary extinct animals.

It is convenient to group together the more typical examples of Early and Middle Paleolithic man under the name *Homo primigenius,* while modern man, who made his first appearance in Late Pleistocene (or Late Paleolithic) time, is called *Homo sapiens.* The nearest living approaches to the Middle Paleolithic type are such as the native papuan

of New Guinea and the bushman of Australia. The native Tasmanian, who became extinct during the nineteenth century, was even more like Middle Paleolithic man.

Earliest Paleolithic man is known almost entirely from the numerous crude stone implements, particularly hand axes and hide scrapers, which he left, but actual bones positively known to be of this age are as yet

Fig. 366. Heads of Neanderthal man (left) and Crô-Magnon man (right) restored. (After J. H. McGregor, courtesy of the American Museum of Natural History.)

unknown. The implements represent the Chellean and Acheulean cultural ages.

Middle Paleolithic man lived during the Mousterian cultural age. He is well represented not only by numerous implements from many localities, but also by bones and practically complete skeletons, in many places. His implements were generally better made and used for more

purposes than those of Early Paleolithic man. Associated ashes, charcoal, and burnt bones, prove that he knew the use of fire.

Middle Paleolithic man is typified by the Neanderthal race, so named because of the skeletons found (1856) in the Neander Valley, Germany. Neanderthal men "were short, bull-necked, barrel-chested individuals, with many features of the bones of the trunk and of the extremities suggesting an affinity with the great apes less remote than that of modern man. The most striking features were, however, those of the skull. The long and narrow brain cases were of moderate size or even large, but flattened down and low; their orbits were surmounted with huge bony brow ridges, behind which the forehead retreated in an ignominious fashion. The jaws were protrusive to the verge of snoutiness; the chin receded practically to a vanishing point; and the teeth were massive, but without canine projection" (E. A. Hooton). Neanderthal man walked with stooping shoulders, and his neck and head were carried forward in the same curvature as the back, so that the head hung forward on the chest. His hands and feet were large and his knees bent. His skull was comparatively thick. Neanderthal man "is genealogically the latest to retain several specially apelike characters associated in a single individual" (A. S. Woodward).

In addition to the skeletons found in the Neander Valley, brief mention will be made of a few others. In a cave at Spy, Belgium, two nearly complete skeletons of Neanderthal man have been found. They were associated with remains of characteristic Pleistocene animals. In the Perigord district of southwestern France, there are several caves in which were found relics of man believed to range from Early to Late Paleolithic time. An important discovery (1908) was in a cave at La Chapelle-aux-Saints in southern France. The remains are a nearly perfectly preserved skull together with the lower jaw and many bones of the body. Among the associated animal remains were the reindeer, horse, rhinoceros, ibex, wolf, badger, and boar. This La Chapelle specimen seems to represent a fine typical example of Middle Paleolithic, or Neanderthal, man. Near Krapina in Croatia hundreds of human bones, associated with thousands of bones of other animals, were found in 1899 in a rock shelter. "The skulls are of men, women, and children, and are slightly broader than the later (Neanderthal) ones, with less prominent eyebrow ridges and not quite such massive jaws, but there is the same retreating chin and flat crown" (E. W. Berry). A number of Neanderthal skeletons have recently been found at the base of Mount Carmel and near Galilee in Palestine; Crimea; and Rho-

desia. Mousterian stone implements, without associated human bones, have been discovered in many parts of western Europe, Asia Minor, and North Africa.

The Neanderthal race existed for scores of thousands of years through the third glacial and interglacial stages, and ranged over large parts of western and southern Europe, western Asia, and central and northern Africa.

Late Paleolithic man lived during the Aurignacian, Solutrean, and Magdalenian cultural ages of Late Pleistocene time, that is during the fourth and last glacial stage. He is typified by the Crô-Magnon race which seems to have invaded Europe, probably driving out Neanderthal

FIG. 367. The "Procession of Mammoths"; a painting by Late Paleolithic man in a cave at Font-de-Gaume in west-central France. Note the lack of perspective composition. (After Capitan and Breuil, courtesy of the American Museum of Natural History.)

man. His stone and bone workmanship was the finest of Paleolithic time and he has left records of drawings and pictures in caves (Fig. 367).

Crô-Magnon man is classed with modern man as *Homo sapiens*. He was longer in arms, legs, and head than modern man. The average size of his head was fully as great as that of present-day man, but somewhat less than that of the highest types of the latter. Both skull and forehead were high, but his cheek bones were unusually wide, causing him to have a broad face. He had a well-formed chin. His brow ridges were fairly heavy. He stood taller and straighter than Neanderthal man.

Numerous skeletons of Crô-Magnon man have been found in various parts of Europe. These are usually associated with many bone and stone implements, and with bones of various animals, especially horses. Some of the best finds have been made in or near Aurignac, Solutré, Grimaldi, and Dordogne Valley in France, and at Předmost in Czechoslovakia.

An interesting feature concerning Late Paleolithic man is the fact that many caves which he occupied have their walls decorated with drawings and even pictures in colors—veritable art galleries. One of the finest examples is the Altamira cavern in northern Spain. "As we gaze at the pictures one of the first things to impress us is the excellence of the drawing, the proportions and postures being unusually good. The grand bison and the charging boar are masterpieces in this respect. The next observation may be that, in spite of this perfection of technique, there is no perspective composition—that is, no attempt to combine or group the figures (Fig. 367). . . . In addition to these remarkable sketches in colors, the other walls of Altamira have numerous figures in black outline and also engravings. . . . It is also clear that the work of many different artists is represented, covering a considerable period of time. The walls show traces of many other paintings that were erased to make way for new work" (C. Wissler).

Many other caves containing works of art have been discovered in northern Spain and in France.

The appearance of true man "was an event which in importance ranks with the advent of life upon the planet, and marks a new manifestation of creative energy upon a higher plane. There now appeared intelligence, reason, a moral nature, and a capacity for self-directed progress such as had never been before on earth" (W. H. Norton).

*Neolithic Man.* So far as known the Late Paleolithic passed gradually into the Neolithic or recent stone age when man was more highly developed and similar in structure to present-day man. The stone implements of Neolithic man were usually more perfectly made and often polished. Neolithic man lived for thousands of years during the earlier post-Glacial or Recent epoch, but various less civilized people of today still practise Neolithic culture. "The remains of Neolithic man are found, much as are those of the North American Indians, upon or near the surface, in burial mounds, in shell heaps (the refuse heaps of their settlements), in peat-bogs, caves, recent flood-plain deposits, and in the beds of lakes near shore where they sometimes built their dwellings upon piles. . . . Neolithic man in Europe had learned to make pottery, to spin and weave linen, to hew timber, and build boats, and to grow wheat and barley. The dog, horse, ox, sheep, goat, and hog had been domesticated."[1] Neolithic culture spread over most of Europe, and it gradually passed into the (present) historic age. This culture may be

[1] W. H. Norton: *Elements of Geology*, p. 448.

said to have marked the beginning of true civilization approximately 20,000 years ago.

*Antiquity of Man in North America.* There is no well-proved evidence for man's existence in North America earlier than very Late Pleistocene time. "The association of man in America with certain fossil forms is unquestioned, and there is a growing body of evidence strongly suggesting his contemporaneity with a considerable number of mammalian types no longer living. Such contemporaneity, however, by no means indicates any remote geological antiquity for man on this continent, and there is at present almost no paleontological evidence suggesting his presence here at a time earlier than that of the withdrawal of the last Pleistocene ice sheet" (A. S. Romer, 1935).

Among the most interesting discoveries in North America were the finding of what are claimed to be human (stone) implements, associated with remains of extinct animals (presumably Late Pleistocene), near Frederick, Oklahoma; Folsom, New Mexico; and Colorado, Texas. At Vero, Florida, human remains are associated with those of extinct animals (possibly Late Pleistocene). In all of these cases it is a problem as to whether man lived in Late Pleistocene time, or that the associated remains of now extinct animals represent forms which lived on into post-Pleistocene time.

As late as 1931 a human skeleton was unearthed from glacial lake clays in Minnesota. The skull, plainly belonging to *Homo sapiens*, has extra-large teeth and distinct mongolian affinities. The fact that the bedding of the clay was undisturbed shows that the person died while the lake existed in front of the waning ice sheet, some 15,000 to 20,000 years ago.

# APPENDIX

## ORGANIC EVOLUTION [1]

### Definition

Organic evolution may be defined as orderly change among organisms, both plants and animals. It "means that the present is the child of the past and the parent of the future" (J. A. Thomson).

### Evidences of Evolution

**Geological Evidence.** One of the plainest and most important lessons taught in this book is that, as the hundreds of millions of years of geological time passed, both plants and animals, starting from low-order forms, generally became biologically more complex in structure. Not all changes in the history of living things have been progressive. In some cases there have been setbacks or retrogressions among groups of organisms. The great, general changes in evolution have, however, been progressive, bringing into existence a succession of higher (or more complex) plants and animals in almost, if not quite, the order of geological time, as clearly shown in the table in Chapter XV. Man, the most complex of all known organisms, appeared in very late geological time.

More in detail, various classes and smaller groups of animals furnish remarkable illustrations of change through longer or shorter parts of geological history. Mention may be made of the chambered cephalopods (Cambrian to present), insects (Pennsylvanian to present), fishes (Silurian to present), placental mammals (Cretaceous to present), and man (Quaternary). Thus there is overwhelming evidence of evolution in the geological record. Just what evolutionary changes the future will witness we do not know, but we are quite certain that creation is not a finished act.

[1] The reader who may wish to go more fully into this subject will find an authoritative, popular account called "The Story of Evolution" in Thomson's "The Outline of Science."

**Anatomical Evidence.** "There is also anatomical evidence of a most convincing quality. In the forelimbs of backboned animals, say, the paddle of a turtle, the wing of a bird, the flipper of a whale, the foreleg of a horse, and the arm of a man, the same essential bones and muscles are used to such diverse results" (J. A. Thomson). Again, the primates, including lemurs, monkeys, apes, and man, all have skeletons built on the same plan almost bone for bone. Not only the bones, but also many of the body organs are essentially the same. A great many other examples of similarity of structure in allied groups of animals could be mentioned. Such remarkable similarities certainly indicate kinship of animals within the groups.

**Embryological Evidence.** Still other convincing evidence of organic evolution is found in the life histories of individuals. It is a law of life that every individual, including the human being, begins as a single cell and passes through a series of changes before reaching a full-grown condition. Thus the frog (an amphibian) lays eggs in water. The tadpoles hatched from the eggs are distinctly fishlike with gills and tails, but without legs. In time the gills and tails disappear, lungs and legs are formed, and the creature can live on land. It is plain, from the geological record, that amphibians not only appeared later than fishes, but also that they evolved from the fishes. Such a brief repetition of various features of a race or group in the life history of the individual is called the *law of recapitulation*. It is more or less true of nearly all organisms. Even in man's pre-natal history the embryo is, in its early stages, remarkably similar to the embryos of such diverse forms as frog, chicken, and dog. Here again we have striking proof of the remarkable kinships of large groups of animals.

## Factors of Evolution

We should not be led astray by those who refuse to accept evolution as a fact because its exact cause is not known. It would be just as logical to assert that there was no Quaternary Ice Age because we do not know precisely what caused it. In the scientific world the *fact* of evolution is certain—evolution is a law of nature—but the *factors* or *causes* of evolution are by no means well understood. Some of the most commonly suggested factors are the following:

**Heritable Variations.** It is well-known that the offspring is essentially like the parent, but it is also true that no two animals of the same species, however closely related, are precisely alike. Marked

"heritable novelties or variations often crop up in living creatures, and these form the raw material of evolution. These variations are the outcome of changes in the germ cells that develop into organisms" (J. A. Thomson). Just how such germ-cell changes occur is not positively known, but they are probably controlled by the so-called *genes* which are tiny particles in the germ cells. Through hereditary tendency a marked variation may become more or less established or fixed in a line of descendants.

**Natural Selection.** In the world of living things remarkably few seeds or germ cells ever develop into individual plants or animals, and, of the individuals produced, an amazing number die when young. Diseases, lack of food, and extreme temperatures exact heavy tolls. Competition among plants and animals is more or less severe—often very severe. Only those survive which are well adjusted to the conditions under which they live. Such a natural process, involving "survival of the fittest," is known as *natural selection.* By such a struggle for existence nature gets rid of the unfit, and leaves the fit to live and reproduce. Because of the tendency toward variation in a species, an occasional individual may appear with some new feature which enables it to face the competition for existence better than the other individuals of the same species. When such a variation is heritable, a new and better breed of plant or animal results. Animal and plant breeders watch for such variations, and, by proper artificial selection and mating, they have produced remarkable changes among plants and animals.

**Influence of Environment.** As pointed out in numerous places in the pages of this book, the earth's surface has undergone a very great number of changes at many times and in many regions. Some of these changes were small, but others were profound, affecting large parts of continents. The coming and going of mountains, the advances and retreats of the seas, the spread of vast ice sheets, times of extensive volcanic activity, and many other physical changes, often produced important changes in the habitats of living things, involving alterations in climatic conditions and food supply. Animals and plants have been forced to adapt themselves to the new conditions or become extinct. The record of the rocks shows that race after race failed in the struggle, while others went on, steadily advancing in complexity of structure or adaptability to changing environments as the ages rolled by. It is probably true that not a species of plant or animal from the Paleozoic era has survived to the present day, and very few from the Mesozoic era.

Some of the most profound evolutionary changes among organisms

accompanied the tremendous physical changes at the end of the Paleozoic and Mesozoic eras. The increasing cold of later Cenozoic time, reaching a climax during the Ice Age, also marked a time of great evolutionary changes.

## Evolution of Man

The following statement, issued in 1926 by the Council of the American Anthropological Association, clearly shows the position of the modern scientific world in regard to organic evolution, particularly with reference to man:

"In view of the dogmatic objections raised against the theory of evolution the Council of the American Anthropological Association have thought it advisable to formulate the present position of scientific inquiry.

"The plants and animals belonging to early periods of the earth's history show that the forms have not remained the same for any length of time. The changes that have occurred are of such character that we are compelled to consider the later forms as descendants of older forms. No form of living being has remained the same through the ages. The evidence of past times is corroborated by the structural and developmental analogies observed in related forms, proofs of a gradual differentiation from common ancestral forms.

"The minute structure of all living matter is alike and shows that all organisms, from the lowest to the highest, must be considered as a unit.

"Man has succeeded in producing a variety of forms of domestic animals and cultivated plants which differ from their ancestors. Our success, accomplished in a very short period, indicates that in long periods nature will produce more fundamental changes.

"Man is part of the animal world. In all respects his anatomical structure conforms to that of the rest of the animal world. His prenatal life closely parallels that of the higher mammals. The same influences that control their development after birth control him and he responds in a like manner to the environment in which he is placed. Prehistoric archeology has shown that, in the course of the ages, man has undergone great changes in physical type and that ancient man differed from modern races, the more so the more ancient the remains.

"Local types of man have developed on every continent and their existence proves that changes in the heritable characteristics of racial groups are affected in the course of time.

"We must conclude that the bodily form of man as well as that of animals and plants has changed and is still changing, not in the course of centuries, but in longer periods.

"The exact cause of changes in the form of organisms and the conditions under which they occur, as well as the causes making for stability, are still imperfectly known. The principle of change has been so well established that it should become the common property of mankind."

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